Technical Report GL-99-3
March 1999

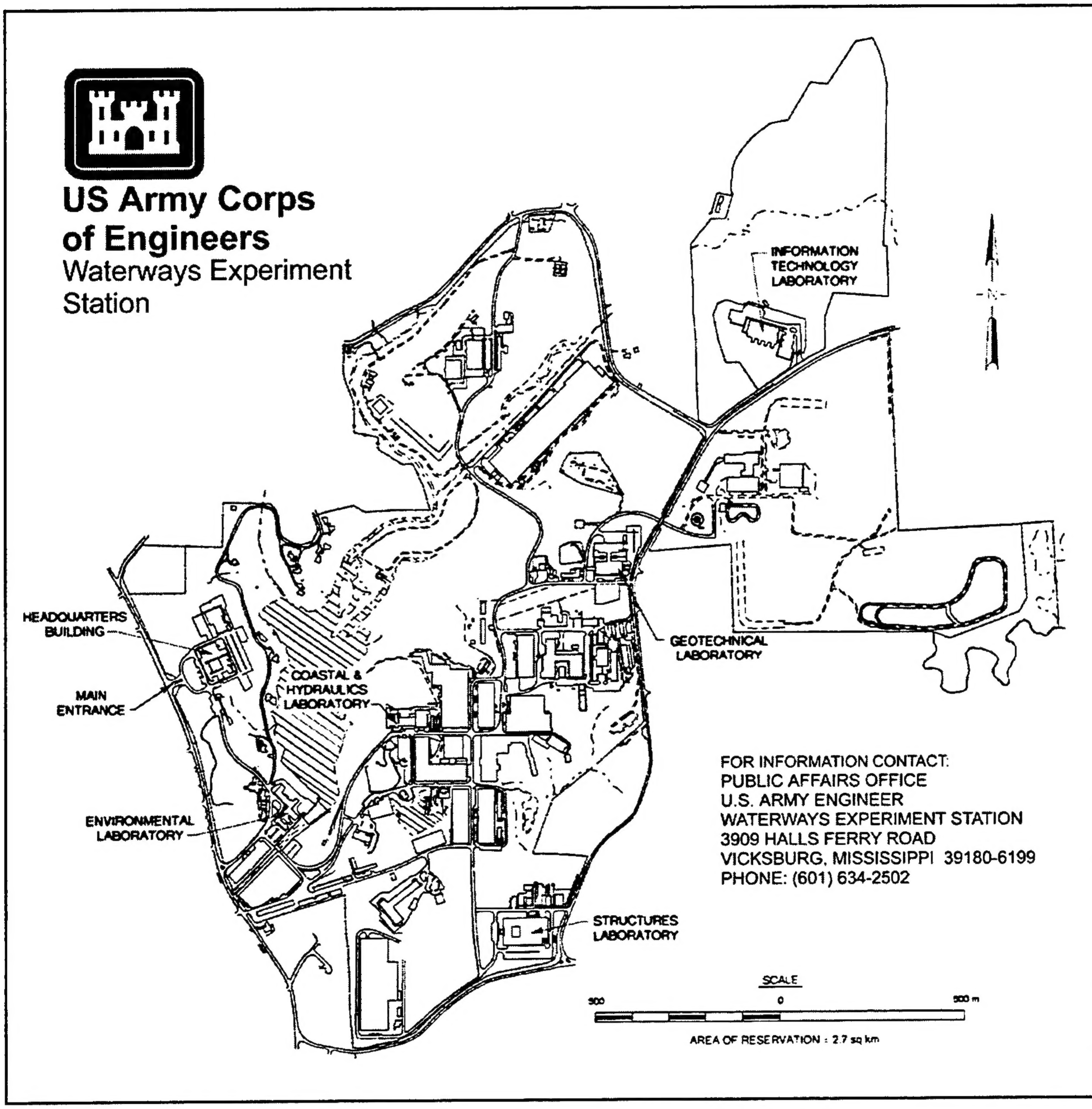
US Army Corps of Engineers
Waterways Experiment Station

Discrete Fiber Reinforcement of Sands for Expedient Road Construction

by Jeb S. Tingle, Steve L. Webster, Rosa L. Santoni

WES

Prepared for Headquarters, U.S. Army Corps of Engineers



Waterways Experiment Station Cataloging-in-Publication Data

Tingle, Jeb S.
Discrete fiber reinforcement of sands for expedient road construction / by Jeb S. Tingle, Steve L. Webster, Rosa L. Santoni ; prepared for U.S. Army Corps of Engineers.
110 p. : ill. ; 28 cm. -- (Technical report ; GL-99-3)
Includes bibliographic references.
1. Roads -- Design and construction. 2. Fibers -- Testing. 3. Sand --Stability -- Testing. 4. Reinforced sand, Fiber. 5. Soil stabilization. I. Webster, Steve L. II. Santoni, Rosa L. III. United States. Army. Corps of Engineers. IV. U.S. Army Engineer Waterways Experiment Station. V. Geotechnical Laboratory (U.S. Army Engineer Waterways Experiment Station) VI. Title. VII. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-99-3.
TA7 W34 no.GL-99-3

Contents

List of Tables

Preface

The investigation described in this report was sponsored by Headquarters, U.S. Army Corps of Engineers, under Work Unit AT40-MM-501, Work Package 155, "Advanced Materials for Construction of Contingency Pavement." The Army technical monitor was Mr. Robert A. Harris (ATSE-CTE).

This publication was prepared by the U.S. Army Engineer Waterways Experiment Station (WES) based upon experiments conducted during the period May through November 1997. Staff members actively engaged in the planning and implementation of the investigation were Messrs. Steve L. Webster, Jeb S. Tingle, Thomas P. Williams, Donald Smith, and Richard Bradley, and Ms. Rosa L. Santoni, Airfields and Pavements Division (APD), Geotechnical Laboratory (GL). Technical assistance was also provided by Messrs. C.W. Pritchard, Dennis J. Beausoliel, George Walker, and Charles Wilson, Directorate of Public Work, WES. This publication was prepared by Messrs. Tingle, Webster, and Ms. Santoni under the general supervision of Dr. W. F. Marcuson III, Director, GL, and under the direct supervision of Dr. David W. Pittman, Chief, APD, and Dr. A. J. Bush III, Chief, Technology Application Branch, APD.

Acting Director of WES during publication of this report was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

All numerical data reported in this document are recorded in non-SI units to accurately reflect the method of measurement. Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
inches (in.)	0.0254	meters (m)
feet (ft)	0.3048	meters (m)
square inches (sq in.)	6.4516×10^{-4}	square meters (m^2)
square feet (sq ft)	0.0929	square meters (m^2)
square yards (sq yd)	0.8361	square meters (m^2)
cubic feet (cu ft)	0.0283	cubic meters (m^3)
pounds (mass) (lb)	0.4535924	kilograms (kg)
kips, (1,000 lb)	0.4535924	1,000 kilograms (1,000 kg)
tons (mass)	0.9072	metric tons (tonnes)
pounds (force) per square inch (psi)	6.894757×10^{-3}	megapascals (MPa)
pounds (force) per square foot (psf)	47.88026	pascals (Pa)
pounds (mass) per cubic foot (pcf)	0.157	kilonewtons per cubic meter (kN/m^3)
square inches (sq in.)	6.4516×10^{-4}	square meters (m^2)
square yards (sq yd)	0.8361	square meters (m^2)
gallons (gal)	3.785	liters (L)
gallons per square yard (gsy)	4.5273149	liters per square meter (L/m^2)
miles per hour (mph)	1.6093	kilometers per hour (km/h)
degrees Fahrenheit (°F)	Subtract 32 and multiply by 0.5556	degrees Celsius (°C)
foot pounds per cubic foot ($ft\text{-}lb/ft^3$)	0.0479	kilonewtons per square meter (kN/m^2)

Executive Summary

The experiment evaluating the fiber stabilization of sands presented in this report was composed of an extensive laboratory study and two field experiment sections. The entire experiment was conducted during the period May through November 1997 by the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The laboratory experiment was designed to identify the effect of different variables on fiber-stabilized specimens. The field experiment sections were constructed and trafficked to verify the performance of each experiment item when subjected to wheeled military vehicle traffic. A summary of each material investigated and its performance is presented in this report. An analysis of the field data was conducted to determine the potential of these expedient construction materials under actual load conditions.

The results of the laboratory and field experiments revealed the following:

a. All of the fibers effectively stabilized the six different sand materials in the laboratory. The performance of the various fiber types from best to worst was as follows: fibrillated, tape, monofilament, and mesh. The field experiment sections demonstrated significant performance enhancement in both concrete sand and Yuma sand. The field experiment revealed that tape fibers were susceptible to being pulled out of the stabilized layer.

b. A 2-in. fiber length was determined as the optimum length for fiber reinforcement of sands in the laboratory. Shorter fibers were ineffective, and 3-in. fibers performed similar to the 2-in. fibers. Fiber denier had no significant effect on material performance. These results were supported by the data from the field experiments.

c. The laboratory results indicated that a fiber content of 0.6 to 1.0 percent by dry weight of material would ensure that the stabilized material exhibited strain hardening behavioral characteristics. The field experiment demonstrated that 0.8-percent fibers provided adequate structural support.

d. The laboratory data indicated that fiber stabilization of sand materials would be effective in silty sand materials as well as clean sands. The data also indicated that the fiber reinforcement of sands would be beneficial in both dry and wet of optimum conditions.

e. The field experiment demonstrated the need for a surfacing that will keep the fibers from being "pulled out" of the stabilized surface layer. Three spray-on surfacings were evaluated; Road Oyl performed the best, followed by Pennzsuppress D, and Cousins Pine Sap Emulsion which caused several application problems. A plastic hexagonal mat also provided adequate protection against "fiber pullout" but provided no additional structural support.

f. The following material properties were identified for use when designing pavements with fiber-stabilized sand materials: an effective California bearing ratio (CBR) of approximately 35 percent, a composite modulus of elasticity of approximately 50,000 psi, and a Poisson's ratio of 0.35.

Detailed material information is provided in Chapters 2 and 3 of this report. Chapter 2 describes the laboratory investigation. Chapter 3 presents the field experiments and their results. Conclusions and recommendations are shown in Chapter 4. Tables are incorporated within the individual chapters. Figures and photos follow the report text.

1 Introduction

Background

Military operations in remote locations around the world continue to identify the requirements for improved infrastructure materials and construction techniques. Military engineers are increasingly faced with the task of quickly constructing roads and airfields in remote locations with minimal resources. Logistics-Over-The-Shore (LOTS) operations have also identified the requirement for expedient road construction materials for use in across-the-beach applications. The ability of the military to project forces into the theater of operations is dependent upon its ability to rapidly develop infrastructure for the shipment of troops and supplies. Many regions of the world do not possess adequate supplies of quality aggregates for constructing these facilities. Importing quality construction materials into remote locations, quarrying local material sources, or beneficiation of available materials is both time consuming and costly. Furthermore, diminishing supplies of obsolete, expedient road construction materials in the military's inventory has led to the investigation of new road construction materials. The U. S. military requires a means of rapidly constructing roads and airfields in the theater of operations in a cost-effective and timely manner.

The U.S. Army Engineer Waterways Experiment Station (WES), as the lead Department of Defense laboratory for airfields and pavements research, was tasked to identify and evaluate potential construction materials for use in remote regions of the world. Preliminary research efforts conducted by WES under projects funded by both the U.S. Army and the U.S. Air Force have identified discrete fibers as a potential material for the expedient construction of roads and airfields. The stabilization of indigenous materials with discrete fibers has indicated significant load-carrying capabilities in previous research.

A brief review of related literature indicated that various laboratory investigations have been conducted on fiber-reinforced granular materials, but these investigations did not focus on the design and construction of roads or airfields. The majority of the literature identified improved soil strength properties through laboratory testing without field verification of their results. The investigations agreed that the inclusion of randomly distributed, discrete synthetic fibers increases the load-bearing capacity of sands and improves other engineering properties such as shear modulus, liquefaction

resistance, and particle interlocking (Maher and Ho 1994, Arteaga 1989, and Freitag 1986). Furthermore, the improvement of the engineering properties of sand materials was determined to be a function of fiber type, fiber length, fiber content, and orientation (Gray and Al-Refeai 1986, Arteaga 1989). The recommendations of these laboratory studies concerning the optimum values of the key variables are inconsistent.

WES began investigating discrete fiber stabilization for road construction in 1990. Early WES efforts indicated that fibrillated polypropylene fibers could be effectively mixed with a high plasticity clay (CH) material using standard field mixing equipment (Brabston 1991). This study also indicated that smaller fibers (1 in.) were more effectively distributed by the rotary mixer than were larger fibers (2 and 4 in.). A circular experiment track was constructed in a joint research study between WES and Synthetic Industries which evaluated the structural benefits of fiber stabilizing a silty sand, a lime-modified CH clay, and a cement-modified sand (Grogan and Johnson 1993). The results of the experiment indicated that the inclusion of fibers significantly improved the material performance under the applied traffic. Ahlrich and Tidwell (1994) attempted to use the Corps of Engineers' gyratory testing machine to mechanically stabilize a plastic clay and a beach sand with monofilament and fibrillated fibers. This study indicated that neither fiber type successfully stabilized the clay material, but both fiber types enhanced the properties of the sand material. A significant conclusion of this study was that optimum performance in the sand material was achieved with a 2-in. monofilament fiber at a dosage rate of 0.5 percent by dry weight. In late 1994, WES conducted a laboratory test designed to evaluate the rut resistance of a fiber-stabilized silt and high-plasticity clay using a three-wheel rut-testing device (Shoenberger et al. 1997). Results of these tests were inconclusive.

An evaluation of the previous research and literature indicated enhanced performance of fiber-stabilized sands but mixed success when attempting to stabilize fine-grained materials. WES continued its investigations of fiber stabilization in 1996 when it conducted a laboratory experiment to determine the optimum dosage rate for a 2-in. monofilament polypropylene fiber in a typical concrete sand. The results of the laboratory investigation led to the validation of results through full-scale field experiments (Webster and Santoni 1997). The laboratory results indicated that 0.8-percent fibers by dry weight of material was the optimum dosage rate for a 2-in. monofilament polypropylene fiber. The field experiments identified Road Oyl, a by-product of the paper industry, as a potential surfacing for fiber-stabilized roads and airfields. Webster and Santoni reported that an 8-in. layer of fiber-stabilized sand with a spray-on surfacing could easily support 500 military truck passes with very little damage to the pavement. These field experiments also reported that a 12-in. layer of fiber-stabilized sand in which the Road Oyl was admixed into the top 4 in. could support up to 1,000 passes of a C-130 aircraft. These experiments validated the field performance of fiber stabilization, but they did not address the effects of varying sand types, fiber types, and fiber lengths.

Purpose

The purposes of this report are to (a) describe the laboratory experiments conducted, (b) identify the effect of numerous variables on the performance of fiber-stabilized samples, (c) describe the field experiments conducted, (d) verify the structural load-bearing capacity of fiber-stabilized materials under actual traffic conditions, and (e) present guidance for implementing fiber stabilization into the structural design of pavements.

Scope

This investigation was limited to laboratory and field experiments involving the stabilization of sand materials with discrete fibers. The laboratory unconfined compression tests were conducted on samples derived from a test matrix consisting of six different sand types, four fiber types, five fiber lengths, six fiber deniers, at five different fiber dosage rates. The field experiments consisted of the construction and trafficking of two full-scale experiment sections, each containing seven experiment items. The composition of the experiment items was based upon the results of the laboratory investigation. The first experiment section provided a side-by-side comparison of fibrillated and monofilament fibers at three different dosage rates. Experiment section one also evaluated the performance of three different spray-on surfacings. Experiment section two was composed of items designed to evaluate the performance of tape, monofilament, and fibrillated fibers at a single dosage rate. Experiment section two also included one lightweight mat section to provide a comparison of the performance of fiber-stabilized sands to traditional expedient mat surfacings. Traffic was applied using a 5-ton military truck (6-by-6, M923) loaded to a gross vehicle weight of 41,600 lb. The truck tire pressure was 75 psi. A total of 10,000 channelized truck passes were applied over the test road of experiment section one. A total of 10,000 channelized truck passes were applied over the test road of experiment section two. Initially, 5,000 truck passes were applied, then maintenance was performed prior to applying the additional 5,000 truck passes. The results of the laboratory and field experiments are presented in this report.

2 Laboratory Experiment

Experiment Design

The laboratory experiment described in this report was designed to isolate the effects of sand type, fiber type, fiber length, fiber denier, and fiber dosage rate on the performance of fiber-stabilized sands. The experiment consisted of preparing numerous samples in which a single test variable was altered to quantify its effect on the performance of each sample performance. Each sample was evaluated by conducting unconfined compression tests. These tests were not intended to simulate field conditions but to provide an index for sample performance comparisons. The sample performance was measured in terms of its load bearing capacity and deformation. Table 1 illustrates the laboratory test matrix. In addition to the test matrix, studies regarding moisture content, compaction effort, and silt content were conducted.

Description of Materials

The laboratory experiment described in this report involved six different sands ranging from a fine dune sand to a coarse sand specially blended for use as a fine aggregate in high-strength concrete. The gradation curves for all of the sands used are shown in Figure 1. All of the sand materials were classified according to the procedures described in American Society of Testing Materials (ASTM) D 2487 (1993b). The experiment also evaluated the performance of four different types of fibers. Each material is described and pertinent material properties are identified. Tables 2 and 3 identify the specific material properties of the sands and fibers, respectively.

Test sands

Vicksburg Concrete sand. This sand, hereafter referred to as "concrete sand," was used for the majority of the laboratory testing due to its local availability in large volumes. The concrete sand was a local Vicksburg, MS, sand normally used as fine aggregate in concrete. Its gradation curve is shown in Figure 1. The sand was a pit-run washed sand containing approximately 4-percent gravel sizes and 2-percent minus No. 200 U.S. standard sieve size material. It was classified as a poorly graded sand (SP). Additional material properties for the sand are provided in Table 2.

CTD coarse sand. This sand is specially blended by WES's Concrete Materials Division (formerly Concrete Technology Division or CTD), Structures Laboratory, for use as fine aggregate in high-strength concrete mixes. It was selected to include a sand material with large particle sizes and was also readily available. The gradation curve for this sand is shown in Figure 1. The sand contained approximately no gravel sizes and only 1-percent minus No. 200 U.S. standard sieve size material. It was classified as a poorly graded sand (SP), ASTM D 2487 (1993b). Additional material properties for the sand are also provided in Table 2.

New Orleans filter sand. The New Orleans filter sand was a filter sand obtained from the Mississippi River in New Orleans, LA. This sand is obtained from a uniform deposit and is specially blended for use as a filter media. The gradation curve for this sand is also shown in Figure 1. The sand contained no gravel sizes and no minus No. 200 U.S. standard sieve size material. It was also classified as a poorly graded sand (SP). Other material properties for the New Orleans filter sand are provided in Table 2.

Holland LZ sand. This sand was obtained from the Holland Landing Zone at Fort Bragg, NC. This sand was selected due to its silt content and availability. The gradation curve for this sand is shown in Figure 1. The sand contained no gravel-size particles and approximately 18-percent minus No. 200 U.S. standard sieve size material. It was classified as a silty sand (SM). Table 2 lists additional material properties for the Holland LZ sand.

Tyndall AFB sand. This sand was obtained from Tyndall Air Force Base, Panama City, FL. This sand is characterized as a typical uniform beach sand, and its gradation is shown in Figure 1. The sand had no gravel sizes and no minus No. 200 U.S. standard sieve size material. It was classified as a poorly graded sand (SP). Additional material properties for the sand are provided in Table 2.

Yuma sand. The Yuma sand was obtained from aeolian deposited dunes near Yuma, Arizona. This sand was selected due to its small particle sizes and the presence of a locally available stockpile. The gradation curve for this sand is also shown in Figure 1. The sand contained no gravel-size particles and 7-percent minus No. 200 U.S. standard sieve size material. It was classified as a poorly graded silty sand (SP-SM). See Table 2 for additional material properties for the Yuma sand.

Fibers

Monofilament fibers. The synthetic monofilament fibers used in this investigation were made of polypropylene. The monofilament fibers were tested at three deniers and four fiber lengths. A denier is defined as the mass in grams of 9,000 m of a fiber, and it is used as a measure of fineness as developed by the textile industry. Smaller denier fibers indicate finer strands. Monofilament fiber deniers of 4, 15, and 20 were evaluated to determine the effect of fiber denier on performance. Monofilament fiber lengths of 0.5, 0.75, 1, and 2 in. were tested to determine the optimum length for fiber stabilization. The monofilament fibers used in this experiment were obtained from two sources: Mississippi Materials, Jackson,

MS (0.5 and 0.75 in.), and Synthetic Industries, Chattanooga, TN (1 and 2 in.). Table 3 lists pertinent properties of the fibers evaluated.

Fibrillated fibers. The synthetic fibrillated fibers used in this investigation were also made of polypropylene. The fibrillated fibers were tested at two deniers and four fiber lengths. Fibrillated fiber deniers of 360 and 1,000 were evaluated to determine the effect of fiber denier on performance. Fibrillated fiber lengths of 0.5, 1, 2, and 3 in. were tested to determine the optimum length for fiber stabilization. The fibrillated fibers used in this experiment were obtained from Synthetic Industries. Properties of the fibers evaluated are listed in Table 3.

Tape fibers. The synthetic tape fibers used in this investigation were made of polypropylene. The tape fibers were tested at only one denier and two fiber lengths. The tape fibers used were 2 and 3 in. long, both at 448 denier. The tape fibers used in this experiment were obtained from Synthetic Industries. Table 3 lists the properties of the fibers evaluated.

Netlon mesh fibers. The synthetic mesh fibers used in this investigation were made of polypropylene. These mesh fibers are typically used in drainage and reinforcement applications for athletic fields. The mesh fibers evaluated were composed of 2-in.-wide by 4-in.-long rectangular elements each having open ribs extending from the full perimeter. The square aperture between individual ribs of the extruded mesh was 0.4 in. The mesh fibers used in this experiment were obtained from Grid Technologies Inc., Middletown, RI, a U.S. distributor for Netlon, Ltd, United Kingdom. Table 3 lists appropriate properties of the fibers evaluated.

Preparation of Test Specimens

A review of the available literature concerning the testing of laboratory samples of fiber-stabilized materials indicates that test results are highly dependent upon the sample's preparation. WES developed the following procedures for preparing fiber-stabilized samples using both the lessons from the literature review and the experience gained from previous experiments. There are three critical components to preparing fiber-stabilized samples: moisture control, mixing procedures, and compaction.

Moisture control

The cohesionless nature of sand materials dictates that some moisture is required to adequately mix and mold the samples. Moisture is required to prevent segregation of the fiber and sand during the mixing process and to prevent sample disturbance when removing the sample mold for unconfined compression testing. It should be noted, however, that several test samples monitored from the WES 1997 experiments have been observed to maintain significant load-bearing capacity, even after dry exposure for up to 6 months. Thus, the moisture is required more for the mixing and testing processes than for additional strength characteristics. A moisture control study was performed on each test sand to determine the target moisture content for each

sand. Moisture contents were selected so that small changes in sample moisture did not significantly affect the test results. The target moisture content was selected to isolate the influence of other experiment variables; thus, the optimum moisture content for a particular sample was not used. Figure 2 illustrates the preliminary moisture control results for the concrete sand. All moisture contents were calculated prior to sample mixture and verified after testing according to ASTM D 2216 (1992).

Mixing procedure

The following procedure was used to mix the individual fibers into the sands for laboratory testing. First, an appropriate amount of sand was weighed and placed in a mixing container. Then, the water was measured according to the target moisture content and mixed into the sand in small increments to ensure uniform coverage. The designated fibers were weighed according to the dosage rate desired and mixed in small increments. The added fibers were mixed using a two-bladed mortar mixing bit powered by an electric drill as shown in Photo 1. Once a part of fibers was mixed thoroughly into the sand, an additional increment of fibers was added and mixed until all of the fibers were effectively distributed within the sand material. Extreme care was taken during the mixing process to ensure a uniform sand-fiber mixture. The mixing of fibers into the sand material increased in difficulty as the dosage rate increased. However, the sand-fiber mixtures were relatively uniform for the dosage rates evaluated. Photo 3 shows the fibers mixed into the sand.

Compaction

The compaction procedures described in the literature were extremely variable. Due to the length of the fibers involved in this experiment, a 6-in.-diam, 12-in.-high cast iron mold was selected. The mold consisted of two cast iron halves which bolted together over a cast iron base plate. The standard hammer for a modified Proctor compaction test was used. The 10-lb hammer had an 18-in. drop with a modified 6-in. bottom plate. Each sample was compacted in five layers also in accordance with modified Proctor tests. However, prior to the preparation of the individual test specimens, a limited compaction study was performed to determine the optimum number of blows per layer to use in the experiment. The concrete sand stabilized with 2-in. monofilament fibers at a dosage rate of 0.6 percent of the dry weight of the material was used to determine the compaction energy for the laboratory experiment. This mixture was selected based on previous laboratory experiments. Specimens were prepared at 5, 10, 15, 20, and 25 blows per layer. Unconfined compression tests were used to evaluate the load-bearing capacity of each specimen, and their densities were calculated by dividing their mass by their volume and correcting with oven-dried moisture contents. Figure 3 presents the results of the unconfined compression tests. Based on these results, a compaction effort of 20 blows per layer was selected. This compaction effort was selected as the minimum effort required to minimize sample densification during testing. Compaction efforts greater than 20 blows per layer resulted in negligible increases in sample density and performance. The compaction energy associated with the

selected effort is approximately 7,639 ft-lb/ft^3. Photo 2 illustrates the specimen compaction.

Test Equipment and Experiment Procedure

Test equipment. The test equipment used in the laboratory experiment included the aforementioned compaction equipment, an Instron test machine, an automated data collection device, and two linear variable differential transformers (LVDT gauges). The model 4208 Instron test device is a servo controlled universal testing machine. The Instron is equipped with interchangeable load cells and is capable of both tension and compression testing. The Instron device has a maximum load potential of 60 kips with an accuracy within 1 lb. The device also measures vertical deformation with an accuracy of 0.0001 in. The computerized control system controls the load application rates and duration for a given test sequence. A WES fabricated 6-in.-dia. swivel load plate was used in the experiment to transfer the load from the machine to the specimen. A WES fabricated automated data collection system was used to capture load and deformation data at a rate of 10 points per second during testing. This information was transferred into a spreadsheet for analysis. The two LVDT gauges were calibrated to an accuracy of 0.001 in. and were used to measure the lateral deformation of the test specimens. The data from the LVDT gauges were recorded in ASCII text format and imported into a spreadsheet for analysis. Photo 4 presents the laboratory test setup.

Experiment procedure. The following experiment procedure was used to prepare and test the specimens. First, the contents of the specimens were calculated and the selected proportions weighed. The specimen components were then mixed according to the procedures described previously. Then, each layer of material was placed in the mold and compacted in a steel container according to the procedures described previously. Once the final layer was compacted, the top of the sample was trimmed. The container, mold, and sample were positioned on the Instron device prior to mold removal. The container or pan was used to collect any loose particles during testing. After the mold was removed, the swivel head was lowered onto the test specimen. A 1-lb seating load was applied to the specimen to ensure satisfactory seating of the compression piston. This seating load was considered as the zero load for the determination of load-deformation relationships. Once the seating load was satisfactorily applied, the Instron device was set to initial conditions and the test sequence was initiated. The load was applied at a constant rate of 0.10-in. per minute. Each specimen was compressed until the sample reached 1-in. vertical deformation or collapse. Following the collapse of the specimen or the preset deformation limit, the sample was removed and weighed to determine specimen density. Photos 5 through 7 show selected test specimens at various stages of compression. Moisture content samples were taken from the specimen to determine the actual moisture content of the specimen. The specimens were prepared and tested in accordance with the test matrix presented in Table 1. The unconfined compression tests were performed in accordance with ASTM D 2166 (1991b). The moisture contents were determined according to ASTM D 2216 (1992).

Analysis of Laboratory Test Results

The results of the laboratory experiment were analyzed to isolate the effects of independent variables on the performance of fiber-stabilized samples. The results of the unconfined compression tests were used as an index of sample performance. The performance of test specimens relative to the performance of the control specimen, and each other, provided a means of evaluating the effects of each test variable. A brief evaluation of the reinforcement mechanism is described in the following section. The effects of fiber type, fiber length, fiber content, fiber denier, sand type, silt content, and moisture content on the performance of fiber-stabilized samples are also presented in the following sections. An optimum fiber-reinforcement mixture is identified based upon the results of the laboratory experiment.

Reinforcement mechanism

An analysis of the available literature fails to reveal a complete description of the reinforcing mechanisms by which discrete synthetic fibers stabilize sand materials. The analysis of the results of this laboratory experiment indicated that the primary source of reinforcement stems from the development of tension in the fibers due to particle-fiber contact. The friction developed from the particle-fiber contact initiates the development of tensile forces in the fiber when the material is stressed. Once tension is developed in the fibers, the fibers tend to restrict the movement of particles resulting in a particle-fiber interlocking mechanism. Fibrillated and mesh fibers also provide some aggregate interlock reinforcement when expanded. Additional investigations are required to completely identify the interrelationships between sand particles and synthetic fibers. Figure 4 attempts to illustrate the concepts of fiber reinforcement.

Effect of fiber type

The effect of fiber type was evaluated by testing samples in which the type of synthetic fiber was varied, but all other significant test variables were controlled. The fiber length for these samples was set at 2 in., and the fiber dosage rate used was 1 percent by dry weight of material. The results of the tests indicated that all fiber types significantly improved the load-bearing capacity of all sand types evaluated. The fibrillated fibers performed best in all sands except for the Yuma sand. Tape fibers were only tested in the concrete sand and the Yuma sand due to the limited supply of fibers. The tape fibers performed the best of all fiber types in the Yuma sand and were only slightly outperformed by the fibrillated fibers in the concrete sand. The Netlon mesh fibers provided relatively small increases in the load-bearing capacity of test specimens over the control test samples. The performance benefits of using the Netlon mesh fibers were relatively small compared to the benefits of using the other fiber types. Table 4 presents the performance of various fiber types in different sand materials in tabular form. Figure 5 graphically presents each fiber type's performance in the different sand materials.

Effect of fiber length

The effect of fiber length was isolated by evaluating test samples in which the length of each fiber was varied, but all other significant test variables were controlled. The effect of changes in fiber length was determined for the monofilament, fibrillated, and tape fiber types in the concrete sand. Only one size mesh fiber was available, thus it was excluded from the length evaluation test series. The following lengths of monofilament fibers were evaluated: 0.5, 0.75, 1.0, and 2.0 in. at deniers of 4, 15, and 20. The following lengths of fibrillated fibers were used in the experiment: 0.5, 1.0, 2.0, and 3.0 in. at deniers of 360 and 1,000. Tape fibers were evaluated at 2.0- and 3.0-in. lengths at a denier of 448.

A denier is defined as the mass in grams of 9,000 m of a fiber, and it is used as a measure of fineness as developed by the textile industry. Smaller denier fibers indicate finer strands. The results of the test series indicated that fiber lengths up to 1 in. did not significantly improve the load-bearing capacity of the monofilament test specimens at all three fiber deniers evaluated. The results further indicated that 2-in. monofilament fibers significantly increased the performance of the monofilament fiber-stabilized specimens at the three deniers evaluated. An analysis of the results revealed that fibrillated fiber lengths up to 1 in. only slightly increased the performance of the test specimens for the 1,000-denier fiber. These results also indicated that 2-in. fibrillated fibers significantly increased the performance of test specimens. The 3-in. fibrillated fibers slightly outperformed the 2-in. fibrillated fibers at lower dosage rates. At higher dosage rates, the 2-in. fibrillated fibers slightly outperformed the 3-in. fibrillated fibers. The 3-in. tape fibers outperformed the 2-in. tape fibers at all dosage rates evaluated. Table 5 presents these results in tabular form. Figure 6 graphically compares the performance of each fiber length by fiber type and denier.

Effect of fiber content

The effect of fiber content was evaluated by testing samples in which the dosage rate of the fibers was varied, but all other significant test variables were controlled. Previous investigations conducted by Webster and Santoni (1997) indicated that the optimum dosage rate for fiber reinforcement of concrete sand was between 0.6 and 1.0 percent. The investigation also indicated that dosage rates in excess of 1.0 percent tended to create a "sponge effect" in the test samples in which excessive deformation was required to initiate the development of the sample's load support capabilities. For this investigation, the following dosage rates were selected to evaluate the effect of fiber content on sample performance: 0.2, 0.4, 0.6, 0.8, and 1.0 percent by dry weight of sand. The 2-in. monofilament and fibrillated fibers were evaluated in all sand types at the above dosage rates. The results of the laboratory testing revealed that samples at dosage rates less than 0.6 percent exhibited strain softening characteristics. Specimens prepared at dosage rates of 0.6 to 1.0 percent exhibited strain hardening characteristics. Strain softening is characterized by decreasing load-bearing capabilities with a corresponding increase in strain. Strain hardening is characterized by an increase in load-bearing capability with a corresponding increase in strain.

The optimum sample performance in terms of load-bearing capacity would lie within the zone of strain hardening exhibited by the 0.6- to 1.0-percent test specimens. The results of the laboratory investigation indicated that the optimum dosage rate for stabilizing sands with synthetic fibers lies between 0.6 and 1.0 percent by dry weight of material. Figures 7 through 12 present typical test results identifying the effect of fiber content on sample performance for 2-in. monofilament (20-denier) fibers in each sand type evaluated. Figures 13 through 18 present similar results for the 2-in. fibrillated (1,000-denier) fibers. Figures 19 through 21 present the results for the 2- and 3-in. tape fibers. Figures 22 and 23 show the results of the mesh fiber performance. These figures indicate increasing specimen performance with increasing fiber content up to a dosage rate of 1.0 percent. Furthermore, these tests revealed that sample density decreased with increasing fiber content, supporting the findings of the literature review. Figure 24 indicates the effect of including discrete fibers in concrete sand on the density of the composite material. However, the density of the fine sands, Tyndall AFB sand and Yuma sand, was less affected than the coarse sands. Figure 25 shows the effect on material density of increasing the content of 2-in. monofilament (20-denier) fibers in different sand materials.

Effect of fiber denier

The effect of fiber denier was evaluated by conducting tests on samples in which only the denier of each synthetic fiber was varied, but all other significant test variables were controlled. The effect of fiber denier was evaluated at each available fiber length, and the fiber dosage rate used was 1 percent by dry weight of material. The results of the tests indicated that the load-bearing capacity of the test specimens increased slightly with decreasing fiber denier. The load-bearing capacity of the monofilament specimens decreased by approximately 175 lb from the 4-denier sample to the 20-denier sample, a decrease of approximately 13.5 percent. The load-bearing capacity of the fibrillated specimens decreased by approximately 300 lb from the 360-denier to the 1,000-denier fibers, a decrease in sample performance of approximately 12.5 percent. Figure 6 graphically illustrates these test results. The slight decrease in specimen performance does not appear significant in the samples evaluated, and additional testing involving a broader range of fiber deniers would be required to validate these findings. The increase in performance with decreasing fiber denier may be attributed to the slight increase in the number of fibers per sample due to using smaller diameter fibers when dosage rates are calculated by dry weight.

Effect of sand type

The effect of sand type was evaluated by comparing the performance of samples with similar characteristics in six different sand types. The fiber length for these samples was set at 2 in. The results of the tests indicated that the inclusion of synthetic fibers significantly improved the load-bearing capacity of all sand types evaluated. Table 4 shows the effect of sand type on specimen performance in tabular form. There was no distinguishable difference between the performance of fibers in coarse and fine sands. At a dosage rate of 1.0 percent with a sample deformation of 1 in., the monofilament (20-denier) fibers performed worst in the New Orleans filter

sand and best in the Holland LZ silty sand. Also at a dosage rate of 1.0 percent and 1-in. deformation, the fibrillated (1,000-denier) fibers performed worst in the Yuma sand and best in the Holland LZ silty sand. These results indicated that fiber stabilization of "dirty" sands is feasible and may enhance the overall performance of the samples. These findings led to the initiation of a separate test series in which varying amounts of silt were added to the relatively clean CTD coarse sand to evaluate the effects of silt content on performance. The results of the silt content test series is discussed in the following section. Figure 5 graphically presents the performance of each fiber in the different sand materials at a dosage rate of 1.0 percent. Similar results were obtained at fiber contents of 0.6 and 0.8 percent.

Effect of silt content

The effect of silt content was evaluated by testing samples in which the amount of silt added to the CTD coarse sand was varied, but all other significant test variables were controlled. The 2-in. monofilament (20-denier) fiber was selected for these tests, and the fiber dosage rate used was 1 percent by dry weight of sand. The results of these tests are presented in graphical form in Figure 26. The results of the tests indicated that the inclusion of up to 8-percent silt is beneficial in terms of increased load-bearing capabilities. These tests results also indicated that silt contents in excess of 12 percent may degrade the performance of fiber-stabilized sand materials. These data further indicate that a "dirty" sand can be stabilized with synthetic fibers, and fiber stabilization in "dirty" sands may be more effective than in clean sands.

Effect of moisture content

The effect of moisture content was evaluated by conducting tests on samples in which the moisture content of test specimens was varied, but all other significant test variables were controlled. This investigation was conducted using the same compaction equipment previously discussed, but only five blows were used at each of the five layers. All specimens were tested immediately after compaction. These tests were performed to provide an index to determine the general effect of moisture on performance. The 2-in. monofilament (20-denier) fiber was selected, and the fiber dosage rate used was 0.6 percent by dry weight of material. The results of these tests indicated that sample performance was enhanced by the inclusion of discrete synthetic fibers at all sample moisture contents evaluated. Figure 27 shows the results of the tests conducted to determine the effects of moisture content on sample performance. The results show an increase in sample performance with increasing moisture content above a base moisture content of 2.6 percent up to approximately 9.0 percent. Beyond 9.0 percent moisture, the sample's load-bearing performance was progressively less beneficial. However, all moisture contents evaluated above the base content of 2.6 percent increased sample performance until a moisture content of approximately 14.0 percent was attained (saturation). Saturation for this experiment was defined as the point at which additional moisture was free draining from the specimen. At 14.0-percent moisture or saturation, sample performance was approximately equal to the sample performance at the base moisture content (2.6 percent). These results indicate that fiber stabilization

is more effective when some moisture is present than when the sample is extremely dry of optimum. Furthermore, the sample remains effective at the saturation point of the sample, but its performance is less effective with increasing moisture content beyond the optimum value for that composite material.

Repeatability of laboratory tests

The ability to reproduce test results for specimens with similar compositions was evaluated during the laboratory experiment. The purpose of repeating the laboratory tests was to determine the variability of the test procedures and materials. Two test series were conducted in concrete sand in which 2-in. monofilament (20-denier) and 2-in. fibrillated (1,000-denier) fibers were used to evaluate the repeatability of the test results. Three tests were conducted at each fiber content for each fiber type at each individual fiber dosage rate. The results of these tests are shown in tabular form in Table 6. Graphical representations of the tests results for the monofilament and fibrillated test series are shown in Figures 28 and 29, respectively. The data indicate that the monofilament specimens were slightly less variable overall than the fibrillated specimens. The coefficient of variation was used to compare the variability of different data sets with distinctly different magnitudes. The average coefficient of variations for the monofilament and fibrillated test series were 15.9 percent and 18.6 percent, respectively. The combined average for both test series was 17.3 percent. The variability of the monofilament fibers was slightly less at 0.5-in. deformation than at 1-in. vertical deformation. The variability of the fibrillated fiber specimens at 0.5-in. deformation was slightly higher than at 1-in. deformation. The variability of the test results can be attributed to inconsistencies in the mixing and compaction process. Sources of variability may include: changes in personnel, mixing time, exact layer thickness, and fiber distribution in the sample. In general, however, the variability of the test results was similar to that exhibited by tests conducted to determine the various properties of lime- and cement-stabilized subbase and base course materials. Table 7 presents values for the coefficient of variation for various tests conducted on lime- and cement-stabilized subbase and base course materials. A comparison of the results presented in Table 6 and those reported by Freeman and Grogan (1997) in Table 7 reveals that the repeatability of fiber-stabilized specimens compares favorably to tests conducted on traditionally stabilized materials, although the data in Table 6 are limited.

Summary conclusions of the laboratory experiment

The results of the laboratory investigation indicated that the inclusion of all of the fiber types evaluated in the six sand materials improved the load-bearing capacity of the individual specimens. However, the laboratory investigation indicated that several individual test specimens performed better than others. The high performance of the individual specimens can be attributed to the specimen's composition of the key variables described previously. From the analyses presented in the previous sections, optimum parameters for the fiber reinforcement of sand materials were identified.

The results of the laboratory investigation identified optimum values for each test parameter evaluated. The performance of the various fiber types from best to worst is as follows: fibrillated, tape (limited testing), monofilament, and mesh. The only fiber type that performed poorly was the Netlon mesh fibers. The remaining fiber types would be appropriate for stabilizing sand materials. The analysis revealed that the optimum fiber length for discrete fiber reinforcement was 2 in. Significantly less performance was obtained from specimens composed of the shorter fibers. The 3-in. fibers were typically more difficult to mix and resulted in only minor performance enhancements over the 2-in. fibers. Since performance of the 2- and 3-in. fibers were approximately the same, the 2-in. fibers should be selected to enhance the mixing process and increase the total fiber count for the same weight of material. The results of the fiber content evaluation indicated that the optimum dosage rate for the fiber stabilization of sand materials lies between 0.6 and 1.0 percent by dry weight. Logic dictates that the smallest dosage rate that still provides effective performance be selected. However, the 0.6-percent dosage rate represents the division between the strain hardening and softening performance characteristics. Since strain hardening is the desired condition, 0.8-percent fibers by dry weight of material should be used to ensure that the stabilized material will exhibit strain hardening characteristics. The laboratory test results indicated that fiber denier does not significantly affect the specimen performance, but smaller-denier fibers slightly outperform larger-denier fibers. Additional testing is required to completely quantify the effect of fiber denier on performance. The different fibers performed well in all sand types evaluated, and only minor differences in performance between sands was observed. The fibers tended to perform best in the silty sand and worst in the fine wind-blown Yuma sand. The results of varying the silt content of a coarse sand indicated that up to 8-percent silt is beneficial. Beyond 12 percent, the performance of the fiber stabilized material may degrade below that of the fiber-stabilized clean sand. An analysis of the effects of varying the moisture content of the materials revealed that moisture enhances the composite materials performance. The performance of the fiber-stabilized concrete sand showed enhanced performance in both "dry of optimum" and "wet of optimum" conditions. Thus, maintaining optimum moisture is beneficial, but not essential for obtaining significant reinforcement properties from fiber-reinforced sands. From this discussion of the laboratory investigation's results, the optimum conditions for fiber reinforcement include: (a) a "dirty" sand with 1- to 4-percent silt, (b) the use of 2-in.-long fibrillated fibers at the smallest available denier, (c) a dosage rate of 0.8 percent by dry weight of material, and (d) mixed at the optimum moisture content of the composite material $\pm$ 2 percent.

Table 1
Laboratory Test Matrix

FIBER TYPE (Denier)		SAND TYPE					
	Fiber Length, in.	Coarse Concrete Sand	CTD Coarse Sand	New Orleans Filter Sand	Holland LZ Sand	Tyndall AFB Sand	Yuma Sand
Monofilament (4)	3/4	X					X
	2	X					
Monofilament (15)	3/4	X					X
	2	X					
Monofilament (20)	1/2	X					
	1	X					
	2	X	X	X	X	X	X
Fibrillated (360)	2	X					
	3	X					
Fibrillated (1,000)	1/2	X					
	1	X					
	2	X	X	X	X	X	X
	3	X					
Tape (448)	2	X					
	3	X					X
Mesh	2 x 4	X					X

"X" denotes a test series conducted at the following fiber contents: 0.2, 0.4, 0.6, 0.8, and 1.0 percent by dry weight of material. A blank cell indicates no tests were performed. Samples were compacted in 5 layers at 20 blows/layer with an 18-in. drop of a 10-lb hammer.

Table 2
Sand Properties

Property	Coarse Concrete Sand	CTD Coarse Sand	New Orleans Filter Sand	Holland LZ Sand	Tyndall AFB Sand	Yuma Sand
USCS Classification[1]	SP	SP	SP	SM	SP	SP-SM
Grain size	Medium	Coarse	Medium	Medium	Fine	Fine
Coefficient of uniformity, C_u	2.00	4.44	2.09	6.98	1.44	1.63
Coefficient of curvature, C_c	1.14	0.62	0.95	1.47	0.98	1.16
Mean diameter, D_{50}	0.39	0.53	0.61	0.29	0.21	0.12
Percent finer than #200 sieve	2	1	0	18	0	7
Plasticity index	NP	NP	NP	NP	NP	NP
Fineness modulus	2.31	2.70	2.65	1.40	1.07	0.24

[1] Soils classified according to ASTM D 2487(1993b).
NP = Nonplastic materials.

Table 3
Fiber Properties

Property	Typical Values by Fiber Type			
	Monofilament	Fibrillated	Tape	Mesh
Material	Polypropylene	Polypropylene	Polypropylene	Polypropylene
Shape	Round	Flat-Narrow	Flat-Wide	Round Grid
Color	White	Beige	Beige	Brown
Moisture	nil	nil	nil	nil
Specific gravity, g/cm	0.91	0.91	0.91	0.91
Tensile strength, psi	75,000	45,000	45,000	--
Young's modulus, psi	500,000	700,000	700,000	--
Deniers evaluated	4, 15, and 20	360 and 1,000	448	N/A
Lengths evaluated, in.	0.5, 0.75, 1, and 2	0.5, 1, 2, and 3	2 and 3	2 x 4

Data concerning fiber material properties were obtained from the manufacturers. The following test procedures are referenced:
Polypropylene tested according to ASTM D 4101 (1996), specific gravity tested according to ASTM D 792 (1991), tensile strength tested according to ASTM D 2256 (1997), and Young's Modulus tested according to ASTM D 2101 (Discontinued 1995).

Table 4
Performance of Fiber Types in Different Sands

Sand Type	Performance by Fiber Type[1] (denier), lb				
	Control	Monofilament (20)	Fibrillated (1,000)	Tape[2] (448)	Mesh[3]
Concrete sand	15	1,110	2,115	1,811	423
CTD coarse sand	21	906	1,504	--	--
New Orleans filter sand	0[4]	411	1,832	--	--
Holland LZ sand	67	1,671	2,397	--	--
Tyndall AFB sand	23	1,381	1,983	--	--
Yuma sand	53	1,048	1,316	2,169	302

[1] The data listed are for specimens with 2-in. fibers at a dosage rate of 1.0% and 1-in. vertical deformation.
[2] The tape fibers tested in the Yuma sand were 3 in. long.
[3] The Netlon mesh fibers were 2 x 4 in. at a maximum dosage rate of 0.6%.
[4] Control sample of New Orleans filter sand could not be molded without fibers.

Table 5
Fiber Performance in Concrete Sand

Fiber Length, in.	Fiber Type, Denier	Maximum Load prior to 1-in. Deformation, lb[1] at Fiber Content, %		
		0.6	0.8	1.0
0	Control	15	15	15
1/2	Monofilament (20)	46	60	89
	Fibrillated (1,000)	47	71	92
3/4	Monofilament (4)	107	194	299
	Monofilament (15)	131	195	228
1	Monofilament (20)	321	352	328
	Fibrillated (1,000)	180	241	492
2	Monofilament (4)	490	835	1,315
	Monofilament (15)	450	717	1,248
	Monofilament (20)	483	647	1,110
	Fibrillated (360)	1,169	1,848	2,406
	Fibrillated (1,000)	618	1,401	2,115
	Tape (448)	371	1,927	1,811
3	Fibrillated (360)	1,433	2,025	2,296
	Fibrillated (1,000)	1,455	1,623	1,892
	Tape (448)	1,247	2,304	2,169
2x4	Mesh	423	—[2]	—[2]

[1] Data represent the maximum load of each specimen during the unconfined compression testing up to a deformation of 1 in.
[2] Specimens were not tested at the 0.8- and 1.0-percent dosage rates due to an inability to uniformly mix materials.

Table 6
Repeatability of Laboratory Test Results

Deformation, in.	Fiber Content %	Performance Index (Load), lb			Mean Load lb	Standard Deviation lb	Variance lb^2	Coefficient of Variation %
		Test Series 1	Test Series 2	Test Series 3				
2-in. Monofilament (20-Denier) Fibers								
0.5	0.2	79	86	54	73	16.8	283.0	23.0
	0.4	289	244	257	263	23.2	536.3	8.8
	0.6	431	270	430	377	92.7	8,587.0	24.6
	0.8	569	590	528	562	31.5	994.3	5.6
	1.0	757	750	695	734	34.0	1,153.0	4.6
1.0	0.2	59	73	31	54	21.4	457.3	39.4
	0.4	269	247	223	246	23.0	529.3	9.3
	0.6	483	280	462	408	111.6	12,462.3	27.3
	0.8	640	781	713	711	70.5	4,972.3	9.9
	1.0	1,110	1,067	969	1,049	72.3	5,222.3	6.9
2-in. Fibrillated (1,000-Denier) Fibers								
0.5	0.2	87	52	63	67	17.9	320.3	26.6
	0.4	379	244	200	274	93.3	8,700.3	34.0
	0.6	614	639	680	644	33.3	1,110.3	5.2
	0.8	848	709	781	779	69.5	4,832.3	8.9
	1.0	1,185	645	1,109	980	292.3	85,445.3	29.8
1.0	0.2	39	53	48	47	7.1	50.3	15.2
	0.4	175	168	178	174	5.1	26.3	3.0
	0.6	539	602	902	681	194.0	37,623.0	28.5
	0.8	1,348	1,149	1,119	1,205	124.5	15,490.3	10.3
	1.0	2,089	1,395	2,328	1,937	484.6	234,874	25.0

Coefficient of variation averages: Monofilament (20-denier) = 15.9, Fibrillated (1,000-denier) = 18.6, and combined = 17.3.

Table 7
Summary of Reported Variabilities for Lime- and Cement-Stabilized Subbase and Base Course Materials[1]

Property	Standard Deviation	Coefficient of Variation, Percent	Normality
Unconfined compression strength, kPa	840	15	Not Reported[2]
Compression modulus, MPa	2,400	60	Not Reported[2]
Indirect tensile strength, kPa	340	35	Normal[3]
Tensile modulus, MPa	420	70	Not Reported[2]
California bearing ratio (field), percent	90	30	Not Reported[2]
Plate-load tests, MPa/mm	N/A	70	Not Reported[2]
Dynaflect tests, Mpa	N/A	20	Not Reported[2]

[1] Data taken from Freeman and Grogan (1997).
[2] Reports on variability did not address normality.
[3] Based on the shapes of histograms.
N/A = Limited data or not reported.

3 Field Experiment

Experiment Design

The field experiment for this investigation was designed to validate the results of the laboratory testing under actual field conditions. Two full-scale experiment sections were constructed under shelter in Hangar 4 on the WES reservation. A plan and profile of each experiment section are shown in Figures 30 and 31. In each section, a 12-ft-wide straight traffic lane was designed for channelized traffic over a sand subgrade. Webster and Santoni's (1997) research indicated that an 8-in.-thick stabilized layer was sufficient to support military truck traffic. In addition, the required thickness for an aggregate-surfaced road using Corps of Engineers' (COE) criteria as detailed in TM 5-822-12 (Headquarters, Department of the Army (HQDOA) 1990) given the traffic requirements and subgrade conditions, is approximately 8 in. Thus, for the field experiment, each item was stabilized to a depth of 8 in. Experiment section one was designed to evaluate the field performance of 2-in. monofilament (20-denier) and fibrillated fibers (1,000-denier) at fiber contents of 0.6 , 0.8, and 1.0 percent of the dry weight of material. Section one also contained one item to evaluate the field performance of the Netlon mesh fibers. Experiment section two was designed to evaluate the field performance of 2-in. monofilament (20-denier), fibrillated (360-denier), and tape fibers at a fiber content of 0.8 percent. Section two also evaluated 3-in. fibrillated (360-denier) and tape fibers (448-denier). A plastic hexagonal mat surfacing was placed over 3-in. fibrillated fibers (360-denier) in item 1 of experiment section two to evaluate the mat as a potential surfacing for fiber-reinforced pavements. The fiber contents and fiber lengths used in the field experiment were selected based upon the results of the laboratory investigation. The fiber deniers and sand types used in the field experiment were selected based upon the availability of sufficient quantities of materials. The field investigation was designed to verify the laboratory results while providing information concerning construction techniques and maintenance procedures.

Materials

Sands

The subgrade was composed of the concrete sand previously described. A sand subgrade was selected to simulate a beach environment to address

LOTS issues. The concrete sand and Yuma sand used in the experiment items are those described in Chapter 2. A typical gradation curve for each sand material is shown in Figure 1, and a listing of each sand material's properties is presented in Table 2 in Chapter 2.

Fibers

The fibers used to stabilize the experiment items for the field investigation are those previously described in Chapter 2. Only the following fibers were selected for use in the field investigation: 2-in. monofilament (20-denier), 2-in. fibrillated (360- and 1,000-denier), 3-in. fibrillated (360-denier), and both the 2- and 3-in. tape (448-denier) fibers. Table 3 in Chapter 2 lists the properties of the individual fibers used in the experiment.

Surfacings

Road Oyl. Road Oyl is a resin modified emulsion that is nonwater soluble and has a high bonding strength. It was developed specifically for use in pavement applications, dust control treatment, soil stabilization, and erosion control. It contains selected fractions of natural tree resins combined with a strong bonding agent. It can be field mixed with premoistened materials or diluted with water and sprayed on for surface penetration. It is petroleum-free and can be cold-applied. Road Oyl is environmentally friendly and available for bulk shipments, 55-gal drums and 275-gal pelletized bulk container packaging. The Road Oyl used in the field experiments was purchased in 55-gal drums from Road Products Corporation, Knoxville, TN, for $4.20 per gallon. The bulk price was approximately $1.79 per gallon plus $2.00 per mile per 6,000-gal truck load. Pertinent material properties are identified in Table 8.

Pennzsuppress D. Pennzsuppress D is a water-emulsified resin base composed of strong bonding agents specifically formulated for dust control applications. In addition, Pennzsuppress D is reported to be an effective erosion control product. It is formulated with a blend of wetting agents, emulsifiers, and dispersants to enhance product penetration into the soil. Pennzsuppress D is supplied in either a 4:1 water to concentrate solution or a concentrated form. It can be further diluted with water depending upon soil conditions and application methods. The product contains no asphalt or solvent and is reported to be noncorrosive, nonhazardous, nontoxic, and noncarcinogenic. The quantities used in the field investigation were obtained in 55-gal drums from Pennzoil Products Company, Houston, TX, at a cost of $1.93 per gallon. The bulk price was not identified. Material properties are identified in Table 8.

Cousins Pine Sap Emulsion. Cousins Pine Sap Emulsion is a biodegradable emulsion composed of tree sap, surfactants, and water. Cousins Pine Sap Emulsion was designed for use as a dust suppressant, hydroseeding agent, erosion control media, or as a soil stabilizer. The product can be diluted with water to produce the desired concentration required for various pavement applications. The emulsion is biodegradable, noncorrosive, nonflammable, noncarcinogenic, environmentally safe, and ecologically safe. The quantities used in the field investigation were obtained

in 55-gal drums from Cousins Dust Control, Toledo, OH, at a cost of approximately $2.70 per gallon. The bulk price was not identified. Table 8 lists material properties.

Plastic hexagonal mat. This mat was produced by UmTech-Ecological Technology Company, Inc., Munich, Germany. Mat panels were purchased from the U.S. distributor, Grid Tech, Middletown, RI. These lightweight interlocking mat panels were designed for quick installation to create parking areas and access roadways. The panels are ultraviolet (UV) stable and made from recycled high density polyethylene (HDPE). Each panel weighs 7.05 lb and has a surface area of approximately 2.9 sq ft, resulting in a unit weight of 2.43 psf. The hexagonal form permits road angles of 30, 60, and 90 deg to be created. The cost of test quantities of the mat was $6.00 per square foot. Pertinent information concerning this mat is also presented in Table 8.

Construction

General

The field sections were constructed and trafficked during the period May-November 1997. All work was accomplished by WES personnel using conventional construction equipment. The field experiment was divided into two 12-ft-wide traffic lanes each consisting of seven experiment items as shown in Figures 30 and 31. Experiment section one was constructed and trafficked in the test area first. Experiment section one was then removed, and experiment section two was constructed and trafficked. The test items were constructed over a 28-in.-thick by 20-ft-wide concrete sand subgrade. The concrete sand subgrade was installed over a firm low plasticity clay (CL) soil (California bearing ratio (CBR) > 10) floor in Hangar 4. The sand subgrade material was leveled and compacted with a D4 bulldozer, and each traffic lane was outlined prior to item installation. A sand control item composed only of the concrete sand subgrade material was evaluated under identical conditions in concurrent research (Webster and Tingle 1998). Each constructed item was 32 ft long. The total length of each final traffic lane was 224 ft.

Preparation of materials

The stabilized materials for each experiment item were prepared in a staging area prior to installation. Moisture content samples were taken from the sand stockpiles to calculate the dry weight of the sand and to determine the quantity of water required to obtain the target moisture content. The target moisture content for the concrete sand and Yuma sand mixtures was 8 percent. The appropriate amounts of sand and fibers were calculated based upon the designed fiber content of each item's mixture. The sand material was then weighed out using the difference in weight of an empty and loaded front-end loader. The calculated amount of sand was placed in the staging area where it was leveled to a depth of approximately 1 ft using a D4 bulldozer. Additional water required to obtain the target moisture content was then added to the sand. The selected type and amount of fibers was weighed and uniformly spread across the surface of the moist sand. A self-

propelled rotary mixer was used to mix the fibers into the sand. The rotary mixer made four initial passes across the materials. Then, the material was piled and releveled with a front-end loader. Following the releveling, four additional passes of the rotary mixer were made to mix the fibers into the sand. Photos 8 and 9 illustrate the mixing process. The material was then piled and ready for installation into the experiment sections. Photo 10 shows a uniform mixture of tape fibers and concrete sand.

Experiment section one: Item installation

Prior to the installation of the fiber-stabilized materials into the experiment section, each item was separated using string lines. Within each test item, grade stakes were placed so that a depth of approximately 10 in. of loose composite material could be leveled across the item. The fiber-stabilized sand materials were dumped in place using a front-end loader. Two to four laborers were required to level the loose material in the experiment item to the tops of the grade stakes or 10 in. Photo 11 shows a leveled experiment item prior to compaction. Following the installation of all items in the section, rod and level measurements were used to level the entire section. The grade stakes were then removed, and each item was compacted using five coverages of a vibratory roller. The final compacted layer depth was 8 in. Photo 12 illustrates the compaction of an experiment item.

Item 1 of section one consisted of a mixture of 10 lb of Netlon mesh fibers per cubic yard of concrete sand. This was the maximum amount of mesh recommended by the manufacturer for load support in sand. Items 2 and 3 were composed of a mixture of 0.6 percent 2-in. fibrillated (1,000-denier) fibers and 2-in. monofilament (20-denier) fibers, respectively. The composition of item 4 included 0.8 percent 2-in. fibrillated (1,000-denier) fibers, while item 5 contained a mixture of 0.8 percent 2-in. monofilament (20-denier) fibers. Items 6 and 7 were constructed using mixtures of 1.0 percent 2-in. fibrillated (1,000-denier) fibers and 2-in. monofilament (20-denier) fibers, respectively.

Several lessons were learned during the construction of experiment section one. First, the water required to obtain the target moisture content should be added prior to placing the fibers on the sand. If additional water is added after the fibers are placed, the fibers will tend to stick together during mixing. Secondly, in order to obtain an 8-in. compacted layer of fiber-stabilized material, the grade stakes should be placed at 10 in. of loose material. Additionally, a front-end loader was more effective in mixing the Netlon mesh fibers than was the rotary mixer.

Experiment section one: Surfacing application

Following the compaction of the entire experiment section, the surface was prewet using 1 gsy of water. The spray-on surfacings were then applied using a 50-percent solids solution. The spray-on surfacings were allowed to cure for 24 hours before traffic was applied. Items 1, 2, 3, and 6 were surfaced with Road Oyl which was applied at a rate of 1 gsy. Road Oyl was also applied to the eastern halves of items 4, 5, and 6 at a rate of 1 gsy. The western halves of items 4 and 7 were surfaced with Pennzsuppress D at a

rate of 1 gsy. The Pennzsuppress D surfacing did not set up as firmly as did the Road Oyl Surfacing, but its penetration was sufficient. The western half of item 5 was surfaced with Cousins Pine Sap Emulsion also at a rate of 1 gsy. The Cousins Pine Sap Emulsion broke in the drum and did not penetrate the surface sufficiently. The material tended to form a 1/4-in. layer of sticky black residue which required extensive sand blotting prior to the initiation of traffic on the experiment item. Each surfacing was sprayed onto the compacted fiber-stabilized surface using a 35-gal paint tank filled with 26 gal of material. The material was sprayed through a 5/8-in., 75-ft-long garden hose equipped with a brass nozzle using an air pressure of 20 psi. Photo 13 illustrates the application of a spray-on surfacing.

Experiment section two: Item installation

Following the completion of the traffic application period on experiment section one, each item's materials were removed from the test area. The subgrade material was releveled using the D4 bulldozer. The second 12-ft-wide roadway was divided into seven items using string lines. Grade stakes were then installed to allow a loose layer depth of 10 in. The material mixing and installation procedures described for experiment section one were repeated for the installation of experiment section two's items. The only exception was that Yuma sand was mixed with the fibers for item 7 instead of concrete sand.

All experiment items in section two were constructed at a fiber content of 0.8 percent of the dry weight of the material. Item 1 was composed of a mixture of 3-in. fibrillated (360-denier) fibers and concrete sand. Items 2 and 3 included a mixture of concrete sand and 2- and 3-in. tape fibers, respectively. Items 4 and 5 were constructed using a mixture of concrete sand and 3- and 2-in. fibrillated (360-denier) fibers, respectively. Item 6 incorporated 2-in. monofilament (20-denier) fibers into concrete sand, while item 7 was composed of a mixture of 2-in. monofilament (20-denier) fibers in Yuma sand.

Several additional lessons were learned during the construction of experiment section two. It was observed that some of the fibers did not separate following the mixing process in the Yuma sand. It should be noted that fine sands may require more than four passes per side of the rotary mixer to completely mix the fibers into the sand materials. Additionally, it was observed that the fiber-Yuma sand mixture was more difficult to spread using the front-end loader than the other mixtures. Increased "hand-work" may be required when stabilizing fine sands.

Experiment section two: Surfacing application and installation

Following the compaction of experiment section two, the surface was prewet using 1 gsy of water. The spray-on surfacing was then applied to items 2 through 7 using a 50-percent solids solution of Road Oyl. The spray-on surfacing was applied at a rate of 1 gsy and allowed to cure before traffic was applied. The surfacing material was sprayed onto the compacted fiber-stabilized surface using the same equipment as described in experiment section one.

The plastic hexagonal mat was installed in item 1 directly on the stabilized layer of the traffic lane using two to four laborers. The plastic hexagonal mat required no specialized tools or skills, and it was easily handled by construction personnel. The rate of construction is strictly dependent upon the number of available construction personnel. During construction, a crew of four installed the panels at a rate of 900 ft^2 of roadway per man-hour.

Completed experiment sections one and two

Selected items of the completed experiment sections are shown in Photos 14 and 15. Concrete sand was used as the shoulder material for both experiment sections. All shoulders were 4 ft wide and were used to resist the lateral movement of the experiment items during traffic testing. The final surfaces of both sections were level and smooth prior to the initiation of traffic.

Behavior of Experiment Sections Under Traffic

Application of traffic

Traffic was applied using a M923 5-ton military truck loaded to a gross vehicle weight of 41,600 lb. The individual truck tires were inflated to a 75-psi tire pressure with a contact area of approximately 55.5 in^2. Figure 32 illustrates the load conditions of the test vehicle. Photo 16 shows the test vehicle operating on the experiment section. A total of 10,000 channelized truck passes was applied to items 2 through 7 of experiment section one. Only 2,200 truck passes were applied to item 1 of experiment section one due to the rapid deterioration of the originally constructed roadway. Items 1 through 7 of experiment section two were subjected to 5,000 channelized truck passes with minor rutting resulting. Maintenance was then performed on these items prior to applying an additional 5,000 truck passes. Test traffic was applied by driving the test vehicle (approximately 10 mph) forward over the test items, and then backing the length of the traffic lane in the same wheel path. This resulted in two applications of the traffic load or two passes.

Failure criteria for truck traffic

The failure criteria for unsurfaced or gravel surfaced pavements is 3 in. of permanent deformation or rutting. When the measured rut depth using a straightedge exceeded 3 in., the item was considered failed due to rutting. For this experiment, maintenance was performed when rut depth measurements reached approximately 3 to 4 in.

Maintenance

No maintenance was performed on experiment section one. Traffic was halted on item 1 of section one due to its rapid deterioration. Photo 17 illustrates the severe rutting of the Netlon mesh mixture in item 1. Item 1 was continuously releveled after 2,200 truck passes so that traffic could be continued on the remaining experiment items. Maintenance was performed

on all items of experiment section two to evaluate the effectiveness of the devised procedures. Maintenance on item 1 of section two consisted only of applying five coverages of a vibratory roller in an attempt to relevel the mat surfacing. Maintenance on items 2 through 7 of section two consisted of the following procedure. First, the existing ruts were filled with fiber-stabilized material from stockpiles generated during the construction phase of the experiment. An additional 1/2-in.-thick layer of material was spread across the entire surface of each item. Five coverages of the vibratory roller were used to compact the surface. Following compaction, an additional application of Road Oyl was applied at a rate of 1 gsy to provide a wearing surface. The surfacing was allowed to cure for 24 hrs before traffic was resumed on items 1 through 7 of experiment section two.

Rut depth measurements

Rut depth measurements were recorded at intervals throughout the traffic test period. Measurements were made by placing a metal straightedge across the traffic lane at three locations in each item (item quarter points) and measuring the maximum rut depth using a folding ruler. The measured rut depth included both the permanent deformation and the upheaval within the traffic lane. Photo 17 shows the measurement of rut depths on experiment section one. The average rut depth of each location consisted of the average of the maximum rut depth values from each wheel path. The average of the three locations within each item was recorded as the average rut depth for a given traffic pass level for the entire item. The cross section data were normalized (each subsequent measurement was subtracted from baseline data taken at zero passes) to clearly identify the damage due to the applied traffic.

Figure 33 presents the average rut depth measurements for items 1, 3, 5, and 7 of experiment section one at various traffic levels. Figure 34 presents the average rut depth measurements for items 2, 4, and 6 of experiment section one. Figure 35 presents the average rut depth measurements for all items in experiment section two before maintenance was performed. Table 9 summarizes the detailed rut depth data.

Moisture and density measurements

Moisture and density measurements were recorded for experiment section two following the termination of the traffic test period. Measurements were made using a Troxler 3430 nuclear gauge according to the manufacturer's recommendations by certified personnel. Tests were conducted by using the scraper plate to level the test area, hammering the drill rod into the ground, removing the scraper plate, positioning the gauge over the rod hole, and extending the probe to various depths. A 6-in. probe depth was selected for reporting the material properties of experiment section two. The moisture and density data for section two and the calculated densities of the corresponding laboratory specimens are presented in Table 10 for comparison. A discussion of these results is presented in the following text.

Dynamic cone penetrometer (DCP) measurements

DCP measurements were conducted in experiment section two according to the procedure described in Webster, Grau, and Williams (1992). The DCP had a 60-deg cone tip with a base diameter of 0.79 in. The test procedure involved placing the DCP cone point on the surface and driving the cone into the ground until the base of the cone was flush with the surface. Then, a baseline measurement was recorded to the nearest 5 mm. The 17.6-lb hammer was then raised and dropped 22.6 in. onto an anvil which drove the penetrometer rod and cone into the soil. Measurements of the cone's penetration and the corresponding number of hammer blows were recorded approximately every inch (25 mm) or whenever any noticeable change in penetration rate occurred. Photo 18 illustrates the measurement of pavement strength with depth using a DCP. A DCP strength index in terms of penetration per hammer blow was calculated for each measurement interval. The DCP index was then converted to CBR percentage using the correlation: $CBR = 292/DCP^{1.12}$ where DCP is in mm/blow. DCP data for this report were processed using a Microsoft EXCEL spreadsheet. However, a DCP program developed at WES is available for downloading from the internet at http://pavement.wes.army.mil. Table 11 summarizes the results of the DCP readings taken from experiment section two. Figures 36 and 37 illustrate the results of a DCP test in the sand shoulder material and the wheelpath, respectively. A discussion of the DCP test results is presented in the following text.

Falling weight deflectometer (FWD) measurements

Experiment section two was nondestructively evaluated by conducting FWD tests on each test item, except item 1. The FWD is an impact load device that applies a single-impulse transient load of approximately a 25- to 30-millisecond duration. With this trailer mounted device, a dynamic force is applied to the pavement which results in an impulse loading on an underlying 17.9-in. plate. The applied force and pavement deflections are measured with load cells and velocity transducers, respectively. The drop height of the weights can be varied from 0 to 15.7 in. to produce a force from 6,500 to 54,000 lb. The system is controlled by a microcomputer which also records the output data. Velocities are measured and deflections computed at the center of the load plate and at 1-ft intervals up to 72 in.

The output from the FWD tests was then input into a WES designed Layered Elastic Evaluation Program (LEEP) to isolate each experiment item's representative deflection basin and average impulse stiffness modulus (ISM). The average ISM for the experiment items were lower than typical evaluation limits for LEEP. These data were input into another program, Low Volume, to compute the subgrade CBR for each experiment item. The resulting subgrade CBRs were then compared to DCP data to identify a representative subgrade strength. The representative subgrade strength for experiment section two was determined to be a CBR of approximately 10 percent which was converted to a modulus value of 15,000 psi using a simple conversion relationship of $E=1500 * CBR$. The subgrade modulus represents the composite material modulus of all materials below the stabilized pavement layer. Thus, it represents the composite modulus value of the clean concrete

of the clean concrete sand and the low-plasticity clay below it. This subgrade modulus along with the pavement structural configuration data for each test item were input into the LEEP program to backcalculate the modulus of the fiber-stabilized soil layer. Attempted backcalculation of additional pavement layers was unproductive but did provide composite modulus values for the subgrade similar to the selected value. Setting the subgrade modulus at a value of 15,000 psi provided better correlation between the measured and computed deflections which reduced the overall error of the computed modulus value. The results of the FWD tests are shown in Table 12. A discussion of the FWD test results is presented in the following text.

Posttraffic condition

Photo 19 shows the posttraffic condition of item 1 of experiment section one. This item was in poor condition and would not have supported continued traffic without the continual releveling of the surface. Photos 20 through 25 show the posttest condition of items 2 through 7 of experiment section one. Items 2 through 7 provided adequate structural support to withstand the application of 10,000 truck passes with no maintenance. The fibrillated fibers failed to blend into the surface of items 2, 4, and 6. The fibers in the surfaces of the fibrillated fiber items (items 2, 4, and 6) tended to "pull out" under traffic. Photos 26 through 32 show the posttest condition of items 1 through 7 of experiment section two after the application of 5,000 truck passes following the maintenance of the experiment section. The tape fibers (items 2 and 3) were extremely vulnerable to the "pull out" phenomena. Generally, with the exception of item one of experiment section one, all of the experiment items performed adequately.

Analysis of Field Experiment

The following analysis is based solely on the performance of the selected materials under the test conditions presented in this report. The tests did not include braking or turning traffic conditions.

Experiment item performance

Experiment section one. The Netlon mesh fibers in item 1 averaged 3.6 in. of rutting after only 2,200 truck passes. The material did provide improvement over the control item (concrete sand from Webster and Tingle (1998) which exhibited 8-in. ruts after only 25 truck passes. However, as predicted by the laboratory test results, the field performance of the mesh fibers was substantially less than that of the other fibers evaluated. Figure 33 shows the average rut depth values for items 1, 3, 5, and 7. Items 3, 5, and 7 were designed to evaluate the performance of 2-in. monofilament (20-denier) fibers at fiber contents of 0.6, 0.8, and 1.0 percent, respectively. The field results fail to clearly distinguish between the performances of these three items. Item 7 at 1.0 percent fibers appears to slightly outperform the 0.6- and 0.8-percent fiber contents. The laboratory results indicated that the 1.0-percent item should perform the best, followed by the 0.8-percent item, and then the 0.6-percent item. Figure 34 shows the average rut depth values

for items 2, 4, and 6. Items 2, 4, and 6 were designed to evaluate the performance of the 2-in. fibrillated (1,000-denier) fibers at fiber contents of 0.6, 0.8, and 1.0 percent, respectively. The figure clearly supports the laboratory results which indicated that the 1.0-percent item would perform the best, followed by the 0.8-percent item, and then the 0.6-percent item. As shown in the figure, the 1.0-percent item outperformed the 0.8-percent item, which in turn, outperformed the 0.6-percent item. Furthermore, a comparison of the monofilament (20-denier) and fibrillated (1,000-denier) test results indicates that the fibrillated fibers outperformed the monofilament at all fiber contents except the 0.6-percent dosage rate. All of the monofilament and fibrillated fiber items performed significantly better than the Netlon mesh fibers in item 1. Both figures clearly illustrate substantial rutting early in the traffic period which continued at a much reduced rate as traffic progressed. This indicates that the section could have been compacted better to eliminate this initial densification of the experiment items.

Experiment section two. Figure 35 presents the average rut depths for all of the experiment items included in experiment section two before the maintenance was performed. Item 1 of section two was designed to evaluate lightweight plastic hexagonal mats as a potential surfacing for fiber-stabilized roads. A comparison of item 1 to item 4 reveals no significant structural benefit was obtained by using the mat surfacing. Furthermore, a comparison of the performance of item 1 to a previous investigation is shown in Figure 38 in which the same plastic hexagonal mat was placed over a nonstabilized concrete sand. The figure indicates that the mat performed almost identically with or without stabilization of the material. Thus, confinement of the sand can be achieved by using either the plastic hexagonal mat or fiber stabilization with a spray-on surfacing. An evaluation of the performances of items 2 and 3 indicates that the 3-in. tape fiber slightly outperformed the 2-in. tape fiber. However, the two tape fiber items were among the worst performers in the field. A comparison of items 4 and 5 reveals that there is no distinguishable difference between the field performances of the 3- and 2-in. fibrillated (360-denier) fiber-stabilized materials. Comparing items 6 and 7 shows that the performance of 2-in. monofilament (20-denier) fibers in Yuma sand drastically outperformed the same fibers in concrete sand as shown in Figure 39. These results for monofilament (20-denier) fibers support the laboratory findings shown in Figures 7 and 12. A comparison between the fiber types used in experiment section two indicates that the fibrillated fibers slightly outperformed the monofilament fibers, and the tape fibers performed similar to the monofilament fibers. A comparison of the performances of the 360-denier fibrillated fibers in section two and the 1,000-denier fibrillated fibers in section one indicates that there is no distinguishable difference in the field performance of the two fiber deniers as shown in Figure 40. Figure 35 also verifies the results obtained in experiment section one which indicated inadequate compaction of the experiment items. The figure shows rapid rutting under minimal traffic followed by continued rutting at a much reduced rate of deterioration.

Figures 41 through 43 compare the performance of items of experiment section two before and after the maintenance was performed. Figure 41 compares the average rut depths of items 1, 6, and 7 before and after the maintenance of the section. The figure indicates significantly less rutting in

maintenance procedures were successful in terms of providing continued load bearing support. Figure 42 shows similar results for items 2 and 3. Figure 43 also indicates enhanced item performance following the maintenance performed on the section. These figures combined with Figures 33, 34, and 35 suggest that a significant part of the rutting was caused by the initial densification of the items due to a deficiency in the amount of compactive effort applied to the experiment sections.

Experiment section two structural characterization

Moisture and density data. Moisture and density data were collected from the sand shoulder, the centerline, and the wheelpaths. These data are presented in Table 10. The results of the density tests on the sand shoulder would be similar to the sand subgrade without the overburden of the stabilized layer. The reported density of the concrete sand (shoulder) was less than that exhibited by the control specimen in the laboratory. Although the moisture is factored out by calculating the dry densities of the materials, the added moisture in the laboratory aided in the compaction of the test samples, thereby giving them a greater dry density. A comparison of the densities measured in the wheelpath to those measured in the center-line indicate that the stabilized layer experienced significant densification under the applied traffic. These results support the densification shown in Figures 33 through 35 where the initial rutting of the items occurred quickly due to densification. Additional compaction may reduce the initial densification of the material and thus reduce the overall depth of the rutting. However, further testing may reveal that the inclusion of discrete fibers actually inhibits the compaction of the material while providing increased strength and ductility. Additional research is required to determine if additional compactive efforts would reduce the densification under traffic.

DCP data. DCP measurements were made in the sand shoulder, the centerline, and the wheelpaths. These data were converted to CBR as described previously, and the average CBRs for selected pavement layers are presented in Table 11. The DCPs conducted in the sand shoulder were used to identify the strength properties of the concrete sand subgrade without confinement. A comparison of the DCP values of the centerline measurements and the wheelpath measurements also indicates that densification occurred during traffic. The DCP results indicate a significant increase in CBR due to the stabilization of the upper 8 in. of material. An additional benefit illustrated by the DCP measurements is the confinement of the lower sand layers beneath the stabilized layer. Under confinement, these materials exhibited significantly greater CBRs than those shown from the tests conducted on the shoulder sections at the same depths.

FWD data. The results of the FWD tests were used to backcalculate stiffness modulus values for the stabilized pavement layer of each test item. These data are presented in Table 12. The backcalculated modulus values indicated that the pavement performed similar to a weak flexible pavement. A CBR of 10 percent was assigned to the subgrade to accurately backcalculate the modulus values for the the stabilized pavement layers. This procedure produces the composite modulus of the material above the subgrade. The average backcalculated modulus value for all stabilized layers examined was approximately 53,000 psi. Using the simple correlation

examined was approximately 53,000 psi. Using the simple correlation presented previously, the backcalculated stabilized layer modulus was converted to a CBR of approximately 35 percent. These data agree with the average results obtained from the DCP measurements as reported in Table 11 which indicated an average CBR for the stabilized pavement layer of 34 percent.

Analysis of surfacing materials

The stabilization of cohesionless materials such as sands with discrete fibers requires that some form of surfacing be used to prevent the fibers from being pulled out of the sand during trafficking. The friction forces imparted on the surface of the road by the vehicle tires tends to pull the individual fibers from the sand. The fibers continue to be drawn to the surface under continuous traffic creating a "cotton-like" surface. As the fibers are drawn out of the sand, the reinforcement of the stabilized layer is degraded. This process could be accelerated if the surface of the stabilized layer is permitted to dry out. Continual wetting of the surface could reduce the problem but will not eliminate it. Thus, a surfacing is required to hold the fibers in the sand and prevent them from being pulled out of the surface of the stabilized layer.

In experiment section one, three spray-on surfacings were evaluated: Road Oyl, Pennzsuppress D, and Cousins Pine Sap Emulsion. A lightweight plastic mat was evaluated as a potential surfacing in experiment section two. Figure 44 presents a comparison between the performance of items surfaced with Road Oyl and Pennzsuppress D under identical subsurface conditions. The figure reveals that the Road Oyl surfaces of items 4 and 7 of experiment section two outperformed the Pennzsuppress D surfaces of items 4 and 7. Figure 45 compares the performance of an item in which half was surfaced with Road Oyl and half was surfaced with Cousins Pine Sap Emulsion. The figure shows that similar performance was obtained using both surfacings. However, the problems discussed previously associated with applying and curing the Cousins product were not experienced when applying the Road Oyl.

Construction procedures

The construction of the field experiment sections in this investigation and previous investigations has led to the development of a set of procedures for the construction of fiber-stabilized sand materials. The first step of the construction process is to outline the roadway using a marking system. Moisture samples of the sand material should be taken in order to calculate the desired weights of materials required to produce the desired fiber-sand mixture. Mixing of the materials can be accomplished either in-place or using a staging area as in this investigation.

If a staging area is to be used for mixing, the materials should be weighed using portable scales. The weight of the sand material can be calculated from its density and the volume of the loader's bucket. The sand should be leveled to a depth of approximately 1 ft. If water is available, add water to obtain a moisture content of plus or minus 2 percent of optimum. The fibers

should then be spread evenly across the surface of the sand. Once the fibers are distributed, the fibers should be mixed using four passes of a rotary-mixer. The material should then be piled and spread again to a depth of 1 ft. Four additional passes of the rotary-mixer should be made. Additional passes of the rotary-mixer may be required to provide uniform mixing in fine sands. The material should then be stockpiled for installation. Grade stakes should be placed in the traffic lane at a depth 2 in. greater than the desired layer depth to allow for the compaction of the loose material. A loader can be used to dump the material into the traffic lane and back blade the material to the desired level. Hand leveling may be required for accurate grade control. Once the material is level, the grade stakes should be removed, and the material should be compacted using five to eight coverages of a vibratory roller. Following the compaction of the material, the "spray-on" surfacing should be applied at a rate of 1 gsy. The surfacing should be allowed to cure according to manufacturer's recommendations prior to opening the road to traffic.

For in-place mixing, the quantity of fibers can be calculated from the stabilization depth and area of the traffic lane. The fibers should be evenly distributed throughout the traffic lane, and a minimum of four passes of a rotary-mixer should be made to mix the fibers into the sand. Samples from the traffic lane should be evaluated to verify adequate mixture at depth. Remember to add 2 in. to the desired layer depth to provide for compaction of the loose material. The rotary mixer's depth guides may have to be adjusted to obtain the proper mixing depth. Once the material has been uniformly mixed, the traffic lane should be leveled using a bulldozer or motor grader. Five to eight coverages of a vibratory roller should be used to compact the material. Pneumatic tired compactors or loaded dump trucks can be used for additional compaction to minimize initial rutting. Once compaction is complete, the "spray-on" surfacing should be applied at a rate of 1gsy, and it should be allowed to cure according to manufacturer's recommendations prior to the initiation of traffic.

Design requirements

The mixture design for stabilization of sands should consist of selecting the type and length of fiber to be used, identifying an appropriate fiber content, and the selection of a surfacing if applicable. The results of the laboratory and field investigations indicate that a 2-in. monofilament or fibrillated fiber will provide the desired strength and operational characteristics. The laboratory results indicate that a fiber content between 0.6 and 1.0 percent should be used. The field experiment results suggest that a fiber content of 0.8 percent is sufficient to ensure that the material exhibits a strain hardening behavior.

The thickness of stabilized material used in this investigation was based on the aggregate-surfaced road design as described in Technical Manual 5-822-12 (HQDOA 1990). The inputs for the design procedure included road geometry, design traffic, and material properties. The roadway was designed as a category "IVA", class "F" road using a design sand subgrade CBR of 10 percent. The Corps' criteria indicates that 4 in. of material is required to protect the design subgrade. However, the Corps' thickness criteria are based upon providing an aggregate surface with CBR values of

approximately 80 percent. Since the reported CBR values from the DCP measurements for the stabilized sands in this investigation are somewhat lower than the values used to develop the design curves (35 percent < 80 percent), an additional 4 in. of material was added to the design thickness. This research verified that 8 in. of stabilized material over the subgrade was sufficient to support the design traffic. Additionally, Corps design criteria is typically based upon the development of a 3-in. rut upon completion of the design traffic. The amount of rutting (2.5 to 3.5 in.) exhibited by the field sections indicates that the design thickness of 8 in. was appropriate for the design traffic.

Incorporating the fiber-stabilization technology into the design of flexible pavement systems can be accomplished using either the Corps of Engineers' CBR design procedure or a layered elastic design procedure. For the CBR design procedure, a composite material design CBR of 35 percent should be used for fiber-stabilized sand materials. This value is based on the DCP results shown in Table 11.

Layered elastic design procedures typically require the input of two elastic material parameters, a design modulus of elasticity and a design Poisson's ratio. A backcalculated modulus of elasticity for the fiber-stabilized material was obtained from the FWD data presented in Table 12. A suitable design modulus can also be determined from laboratory testing. A design modulus value of 50,000 psi was selected as an input value for a layered elastic design using the FWD data on selected fiber-stabilized sand items from experiment section two. This value is reasonable given that Yoder and Witczak (1975) reported typical resilient modulus values for granular materials ranging from 15,000 to 100,000 psi. As stated in the literature review, fiber-stabilized sands exhibit greater strength, but not significantly greater stiffness.

Initial attempts to calculate a design Poisson's ratio from the laboratory experiment data were unproductive. Currently, there is no ASTM procedure for measuring Poisson's ratio for large strain materials. Plots of Poisson's ratio versus the axial load of the laboratory test specimens reveal an inelastic behavior. The Poisson's ratio of the fiber-stabilized sands continues to increase with increasing axial load beyond the accepted material limit of 0.5 as shown in Figure 46. Figure 46 indicates that dilation of the specimen occurred during testing. A plot of the mean normal stress versus the volumetric strain verifies the dilation of the material during the test period as shown in Figure 47. This combination indicates that the composite material is performing in an inelastic manner. The large strains exhibited by the specimens prevent an accurate determination of Poisson's ratio using the elastic theory.

Given the inability to calculate a design Poisson's ratio from the laboratory data, a suitable design value of Poisson's ratio was assumed based on engineering judgement. Yoder and Witczak (1975) noted that most layered-elastic design procedures are relatively insensitive to changes in Poisson's ratio. They identified typical values of the ratio for various materials: 0.5 for saturated cohesive materials, 0.4 for unsaturated cohesive materials, 0.3 for cohesionless materials, and 0.2 for cement-stabilized materials. However, they note that the lowest Poisson's ratio used by several

agencies is 0.35. From this information, a suitable Poisson's ratio for fiber-stabilized sands should lie between 0.3 for cohesionless materials (sands) and 0.2 for stabilized materials. Thus, an actual Poisson's ratio between 0.2 and 0.3 should be expected. A Poisson's ratio of 0.35 is recommended as a conservative value for input in layered elastic design. This value will result in design thicknesses slightly greater than those obtained using lower values of Poisson's ratio. A sensitivity analysis using WES's LEDROADS layered-elastic design software was performed to determine the effect of using various values of Poisson's ratio. The results of the analysis revealed that increasing Poisson's ratio from 0.2 to 0.35 only resulted in an increase in the design thickness of approximately 0.51 in.

Surfacing requirements

The requirement for a surfacing for fiber-stabilized roads is attributed to the tendency of the individual fibers to pull-out of the stabilized material under traffic. If no surfacing is provided, the fibers will accumulate on the surface of the stabilized layer resulting in a weakened pavement structure. Two types of surfacings were investigated in the field experiment: a lightweight mat and three spray-on emulsions. The results of the field experiment indicate that the mat surfacing will hold the fibers in the stabilized layer by separating its surface from contact with the vehicle's tire. However, no additional structural benefit should be expected from using the mat surfacing since the sand has already been confined by the fibers. Road Oyl performed the best among the three spray-on emulsions evaluated. The application problems associated with the Cousins Pine Sap Emulsion reduced its assessment as a potential surfacing. The Pennzsuppress D emulsion performed worse than the Road Oyl emulsion but could be considered a legitimate alternative. The recommended application rate for the spray-on surfacings is 1 gsy of a 50-percent solids solution which should penetrate the surface to a depth of approximately 1 in. The spray-on surfacings can be applied using a conventional emulsion distributor. Each material should be allowed to cure for at least 24 hours after which any residual material can be blotted with sand.

Material costs

The material costs include the purchase of the fibers and the the surfacing materials. The costs reported in this investigation are based on limited quantities of materials. The bulk price for most of the materials would typically be much cheaper. The costs for the various fibers are reported in Table 13 in dollars per pound. The costs of the various surfacings are also reported in Table 13 in dollars per gallon and converted to dollars per square yard for comparison purposes. The material costs associated with using new fibers makes this construction technique applicable only under specialized circumstances. If material costs could be reduced by either using recycled materials or negotiating lower costs for bulk purchases, the costs of fiber stabilization would be comparable to the costs of crushed stone.

Table 8
Properties of Surfacing Materials

Property	Spray-On Surfacings: Road Oyl	Spray-On Surfacings: Pennzsuppress D	Spray-On Surfacings: Cousins Pine Sap Emulsion
Stability	Stable	Stable	Stable
Appearance	Brown	Brown	Brown
Solubility in water	Dispersible	Dispersible	Dispersible
Specific gravity, g/cm^3	Not Determined	1.025	0.998
Boiling point, °F	212	212	212
Freezing point, °F	33	40	Unknown
Flash point, °F	400	None	550
Plastic Hexagonal Mat			
Panels consisted of 2.9 ft^2 hexagonal panels weighing 2.43 psf.			

Table 9
Summary of Rut Depth Measurements in Inches[1]

Truck Passes	Item 1	Item 2	Item 3	Item 4		Item 5		Item 6	Item 7	
				East	West	East	West		East	West
Experiment Section One										
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	2.0	1.0	0.8	0.8	1.1	0.8	1.2	0.6	0.9	1.5
200	2.4	1.1	1.1	1.0	1.5	1.0	1.5	0.8	1.0	1.6
400	3.8	1.3	1.4	1.3	1.8	1.3	1.9	1.0	1.2	1.7
800	3.0	1.3	1.4	1.6	1.8	1.4	1.9	1.2	1.7	2.2
1,600	3.6	1.6	1.8	1.4	2.0	1.7	1.9	1.3	1.8	2.4
2,200	--	2.2	2.0	1.9	2.5	2.0	2.5	1.6	2.0	2.6
3,000	--	3.2	3.0	2.5	3.4	2.9	3.1	1.8	2.6	3.6
4,176	--	3.4	3.5	2.6	3.4	3.4	3.2	2.3	3.0	3.8
5,000	--	3.2	3.2	2.6	3.2	3.2	3.1	2.3	2.8	4.2
7,000	--	4.0	3.6	3.0	3.5	3.4	3.2	2.4	3.5	4.0
9,000	--	4.0	3.5	3.2	3.5	3.6	3.1	2.6	3.5	3.6
10,000	--	4.1	3.5	3.0	3.7	3.5	3.2	2.8	3.2	3.7

[1] Rut depth measurements were made using a tenths-of-a-foot ruler and were converted to inches. The data were normalized to isolate the deterioration caused by the applied traffic.

(Sheet 1 of 2)

Table 9 (Concluded)

Truck Passes	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7
Experiment Section Two (Before Maintenance)							
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	1.6	1.3	1.2	1.2	1.1	1.2	0.8
300	2.0	1.6	1.4	1.3	1.2	1.4	1.3
700	2.0	2.2	1.6	1.6	1.4	2.0	1.3
1,500	2.3	2.4	2.3	2.4	2.2	2.6	1.9
2,000	2.2	2.4	2.3	2.2	1.9	2.3	1.8
3,000	2.5	3.0	2.5	2.4	2.3	2.6	1.9
4,000	2.6	3.2	2.9	2.5	2.5	2.6	1.8
5,000	2.8	3.4	3.1	2.9	2.9	3.4	2.2
Experiment Section Two (After Maintenance)							
0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
100	2.2	1.0	1.0	0.7	1.0	1.1	0.7
300	2.3	1.1	1.1	1.0	1.1	1.2	0.7
700	2.4	1.3	1.2	1.0	1.1	1.3	0.8
1,500	2.4	1.6	1.4	1.3	1.2	1.7	1.1
2,000	2.4	1.7	1.4	1.3	1.3	1.7	1.1
3,000	2.5	1.9	1.7	1.3	1.4	1.8	1.1
4,000	2.6	2.4	1.8	1.6	1.6	2.0	1.3
5,000	2.8	2.4	1.9	1.6	1.7	2.2	1.3

(Sheet 2 of 2)

Table 10
Summary of Experiment Section Two Density Measurements[1]

Experiment Item	Average Center-line Dry Density pcf	Average Wheelpath Dry Density pcf	Calculated Laboratory Dry Density[2] pcf
Concrete Sand	104.6[3]		110.4
1	108.4	111.5	104.7
2	108.4	111.0	103.1
3	107.7	112.2	107.6
4	108.4	111.5	104.7
5	107.9	110.6	105.2
6	108.6	112.6	105.1
7	103.4	109.3	97.9
Average:	107.5	111.2	104.0

[1] Field densities were measured using a Troxler 3430 nuclear gauge.
[2] The laboratory densities were obtained by dividing the specimen mass by its volume.
[3] The density measurements for the concrete sand in the field were taken from the shoulders of the traffic lane.

Table 11
Summary of Experiment Section Two DCP Measurements[1]

Experiment Item	Average CBR Stabilized Layer %	Average CBR 12- to18-in. Layer %	Average CBR 18- to 24-in. Layer %
Concrete Sand	6[2]	14	13
1	30	31	41
2	35	38	38
3	40	40	58
4	39	38	46
5	34	33	50
6	31	40	52
7	31	27	43
Average:	34	35	47

[1] DCP measurements were converted to CBR using procedures described in Webster, Grau, and Williams (1992).
[2] The concrete sand measurement was conducted on the shoulders of the traffic lane and represents the upper 12 in. of material.

Table 12
Summary of Experiment Section Two FWD Measurements

Experiment Item	Backcalculated Modulus[1], psi		Load lb	Error[2] %
	Stabilized Layer	Subgrade		
2	39,888	15,000	7,982	17.5
3	28,392	15,000	7,517	13.2
4	21,927	15,000	7,611	10.3
5	24,713	15,000	7,550	11.6
6	113,202	15,000	8,093	24.3
7	89,552	15,000	7,694	17.4
Average:	52,945	15,000	7,741	15.7

[1] Modulus values were assigned to the subgrade using the Low Volume program and backcalculated for the stabilized layer using the LEEP program.
[2] Typical values of error for a weak flexible pavement are 7 to 15 percent.

Table 13
Summary of Material Costs[1]

Synthetic Fibers[2]		Surfacings		
Material	**Cost $/lb**	**Surfacing Material**	**Cost $/gal**	**Cost $/yd^2**
Monofilament	1.44	Road Oyl	4.23	4.23
Fibrillated	1.44	Pennzsuppress D	1.93	1.93
Tape	1.44	Cousins Pine Sap Emulsion	2.70	2.70
Netlon Mesh	9.09	Plastic Hexagonal Mat	$6.00/ft	54.00

[1] Material costs based upon the limited amount purchased for this investigation.
[2] The synthetic fiber costs are based upon a 2-in. fiber length.

4 Conclusions and Recommendations

Conclusions

Laboratory

The results of the laboratory investigation yielded several conclusions concerning the effects of changes in the selected variables on the performance of fiber-stabilized sand materials. These conclusions are listed below.

a. The inclusion of all of the fiber types evaluated in the six sand materials improved the load-bearing capacity of the individual specimens. The performance of the various fiber types from best to worst was: fibrillated, tape, monofilament, and mesh.

b. The optimum fiber length for fiber reinforcement of sand materials is 2 in.

c. The optimum fiber content lies between 0.6 and 1.0 percent by dry weight of material. This range is based upon the development of a strain hardening condition in the test specimen. Below 0.6 percent fiber content, the composite materials evaluated exhibited strain softening characteristics.

d. The fiber denier does not significantly affect the specimen performance. However, the data indicated that smaller-denier fibers appear to slightly outperform larger-denier fibers.

e. All of the fibers successfully reinforced each of the sand materials. However, the stabilization of sands with fibers was more effective in the silty sand. Further investigation revealed that up to 8-percent silt content will increase the effectiveness of the fiber reinforcement.

f. An investigation of the effects of moisture on the fiber reinforcement of sands indicated increased performance with increasing moisture content until saturation is attained. Thus,

specimen performance was enhanced in both "wet and dry of optimum" conditions.

g. Specimen density decreased with increasing fiber content. The density of the fine sand materials was less affected than the coarse sands.

Field experiment

The construction and trafficking of the field experiment sections resulted in several conclusions concerning the validation of the laboratory results, the practicality of the construction procedures, the effectiveness of the maintenance procedures, and the effective structural strength of the stabilized material. These conclusions are listed below.

a. The results of the field experiments indicated that the fiber reinforcement of sand materials was an effective means of stabilization for military truck traffic.

b. The field test results indicated that the fibrillated fibers performed the best, followed by the monofilament, and the tape. The tape fibers performed worse in the field than indicated by the laboratory investigation, but the degradation of performance may be due to the fibers being "pulled out" of the sand during traffic. Furthermore, the Netlon mesh fibers did provide some increased bearing capacity but rutted much more quickly than did the other fiber items.

c. The limited fiber contents evaluated in the field tended to support the laboratory results. The 0.8-percent experiment items provided adequate load support under the applied traffic.

d. The fiber denier did not significantly affect the performance of the experiment items as indicated by the laboratory results.

e. No significant benefit was obtained by using 3-in. fibers instead of the 2-in. fibers. Additionally, 3-in. fibers tended to be slightly more difficult to mix properly.

f. Although only one experiment item contained Yuma sand rather than concrete sand, the results indicated that fiber reinforcement is effective in both sand types. The fiber-reinforced Yuma sand outperformed the same mixture in concrete sand.

g. The construction procedures used were extremely practical and effective. The rut depth and density data indicated that the experiment sections experienced densification under traffic. The densification of the experiment items indicates inadequate compaction. Additional passes of a vibratory roller may be required. The use of a pneumatic tired roller should also be considered.

h. A surfacing is required to reduce the amount of fibers "pulled out" under traffic if the fiber-stabilized material is the surface material. An evaluation of surfacings indicated that the spray-on surfacings were as effective as a mat surfacing. Of the spray-on surfacings, Road Oyl performed the best, followed by Pennzsuppress D, while Cousins Pine Sap Emulsion exhibited a variety of application problems. The plastic hexagonal mat can be used as a surfacing but will not provide any added structural support to fiber-stabilized materials.

i. The maintenance procedures used to repair experiment section two were effective in maintaining the performance of the test items.

j. The effective CBR for design purposes, as determined from DCP measurements, is approximately 35 percent. The composite modulus of elasticity of the fiber-stabilized material is approximately 50,000 psi. A Poisson's ratio of 0.35 is a reasonable estimate for design purposes.

Fiber stabilization of sand materials was confirmed as a legitimate alternative to traditional road construction techniques. The laboratory results revealed the effects of various parameters on performance, and the field experiment verified these results.

Recommendations

The results of the investigation indicate the potential for excellent field performance of fiber-stabilized sands. However, several additional questions need to be answered.

a. The tests conducted did not include the effects of braking and turning on material performance. A field demonstration should be conducted to evaluate the performance of the fiber-stabilized materials under these field conditions. A field demonstration would also provide valuable insight into the durability of the materials and specific construction/maintenance requirements. A field demonstration is required to transfer the technology from the laboratory to the warfighter while monitoring material performance under field test conditions.

b. The following conditions are recommended for stabilizing sands with discrete fibers: (1) a "dirty" sand with 1- to 4-percent silt, (2) the use of 2-in.-long fibrillated fibers at the smallest available denier, (3) at a dosage rate of 0.8 percent by dry weight of material, and (4) mixed at the optimum moisture content of the composite material $\pm$ 2 percent. Road Oyl or Pennzsuppress D should be applied as a surfacing at a rate of 1 gsy using a 50-percent solids solution.

c. The following properties for fiber-stabilized sand materials can be used to design fiber-stabilized pavements using either the Corps' CBR design procedure or a layered elastic design procedure: an effective CBR of 35 percent, a modulus of elasticity of 50,000 psi, and a Poisson's ratio of 0.35.

d. Further investigation is also required to identify the reinforcement mechanisms responsible for the increased material performance.

e. The feasibility of using fiber-stabilized materials as subsurface layers in a flexible pavement system should be investigated.

References

Ahlrich, Randy C., and Tidwell, Lee E. (1994). "Contingency airfield construction: Mechanical stabilization using monofilament and fibrillated fibers," Technical Report GL-94-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Al-Refeai, T. (1991). "Behavior of granular soils reinforced with discrete randomly oriented inclusions," *Geotextiles and Geomembranes* 10, 319-333.

American Society for Testing and Materials. (1991a). "Standard test methods for density and specific gravity (relative density) of plastics by displacement," Designation: D 792, Philadelphia, PA.

________. (1991b). "Standard test method for unconfined compressive strength of a cohesive soil," Designation: D 2166, Philadelphia, PA.

________. (1992). "Standard test method for laboratory determination of water (moisture) content of soil and rock," Designation: D 2216, Philadelphia, PA.

________. (1993a). "Standard test methods for maximum index density and unit weight of soils using a vibratory table," Designation: D 4253, Philadelphia, PA.

________. (1993b). "Standard classification of soils for engineering purposes (Unified Soil Classification System)," Designation: D 2487, Philadelphia, PA.

________. (1993c). "Standard test method for surface strength of paper (wax pick method)," Designation: D 2482, Philadelphia, PA.

________. (Discontinued in 1995). "Standard test method for tensile properties of single man-made textile fibers taken from yarns and tows," Designation: D 2101, Philadelphia, PA.

________. (1996). "Specification of propylene plastic injection and extrusion materials," Designation: D 4101, Philadelphia, PA.

________. (1997). "Standard test method for tensile properties of yarns by the single-strand method," Designation: D 2256, Philadelphia, PA

Arteaga, Carlos Bolivar. (1989). "The shear strength of Ottawa sand mixed with discrete short length plastic fibers," M.S. thesis, Mississippi State University, MS.

Brabston, N. (1991). "Rapid airfield stabilization: phase I," Letter Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Department of Defense, Joint test Director, Joint Logistics Over-the-Shore II (JLOTS II), Test Evaluation. (1985). "Analysis and evaluation report, JLOTS II, throughput test," JLOTS II Test Directorate , Little Creek Naval Amphibious Base, Norfolk, VA.

Department of Defense, Joint test Directorate, Joint Logistics Over-the-Shore III (JLOTS III), Test and Evaluation. (1992). "JLOTS III display determination 91 test report," JLOTS III Test Directorate , Little Creek Naval Amphibious Base, Norfolk, VA.

Freeman, Reed B., and Grogan, W. P. (1997). "Statistical analysis and variability of pavement materials," Technical Report GL-97-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Freitag, D. R. (1986). "Soil randomly reinforced with fibers," *Journal of Geotechnical Engineering* 112 (8), 823-826.

Gray, D. H., and Al-Refeai, T. (1986). "Behavior of fabric versus fiber-reinforced sand," *Journal of Geotechnical Engineering* 112 (8), 804-820.

Grogan, W. P., and Johnson, W. G. (1993). "Stabilization of high plasticity clay and silty sand by inclusion of discrete fibrillated polypropylene fibers for use in pavement subgrades," Technical Report CPAR-GL-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Headquarters, Department of the Army. (1990). "Design of aggregate surfaced roads and airfields," Technical Manual 5-822-12, Washington, DC.

Maher, M. H., and Ho, Y. C. (1994). "Mechanical properties of kaolinite/fiber soil composite," *Journal of Geotechnical Engineering* 120 (8), 1381-1393.

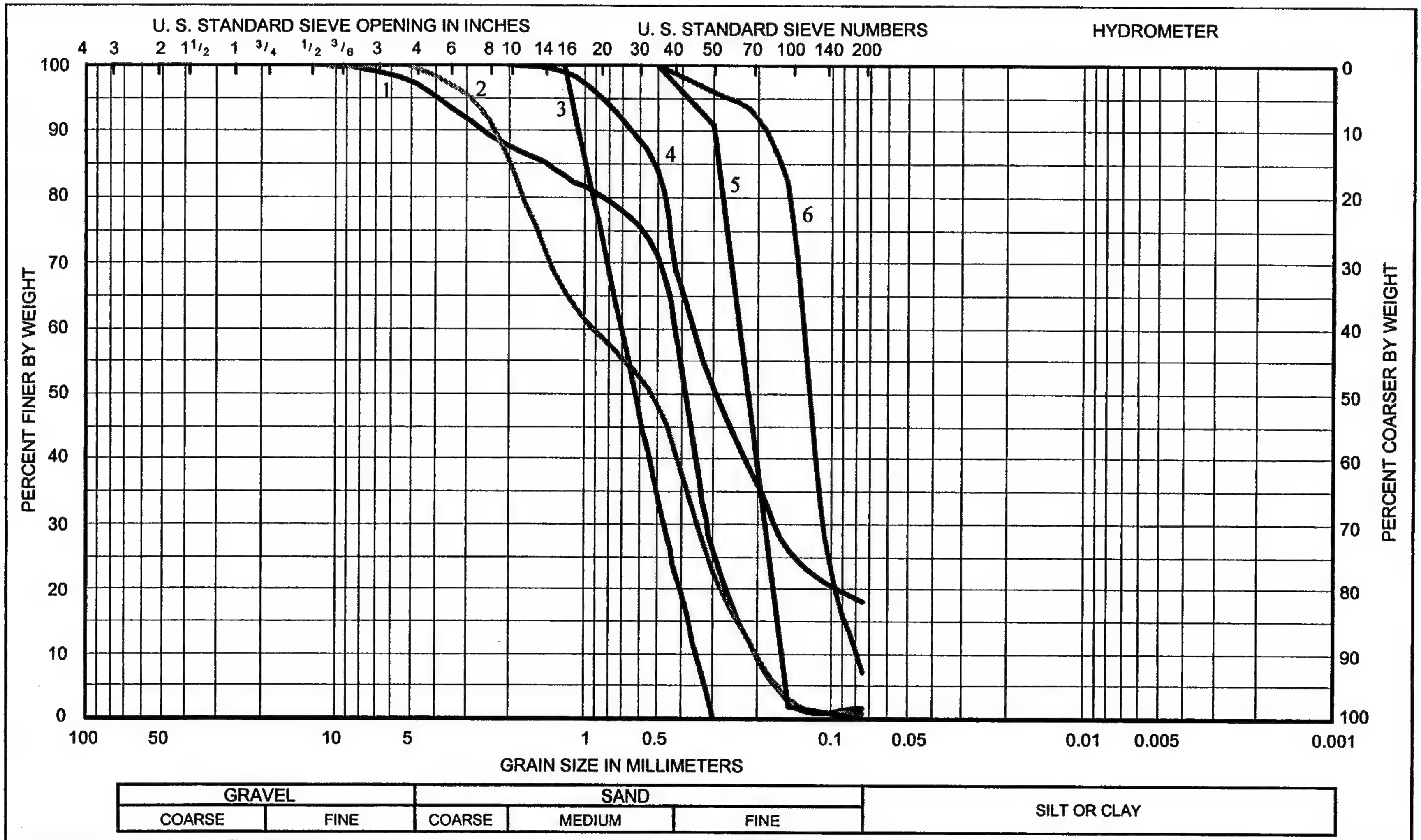
Shoenberger, James E., DeMoss, Tere' A., Williamson, August, and Carr, Harold T. (1997). "Contingency airfield construction: Rut resistance of soils stabilized with monofilament and fibrillated fibers," Technical Report GL-97-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Webster, Steve L., Grau, R. H., and Williams, T. P. (1992). "Description and application of dual mass dynamic cone penetrometer," Instruction Report GL-92-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Webster, Steve L., and Santoni, Rosa L. (1997). "Contingency airfield and road construction using geosynthetic fiber stabilization of sands," Technical Report GL-97-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Webster, Steve L., and Tingle, Jeb S. (1998). "Expedient road construction over sands using lightweight mats," Technical Report GL-98-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Yoder, E.J., and Witczak, M.W. (1975). Principles of Pavement Design, Wiley, New York.



SAMPLE NO.	MATERIAL	CLASSIFICATION	NAT W%	LL	PL	PI
1	Concrete Sand	Poorly Graded Sand (SP) Cu=2.00 Cc=1.14		NP		
2	CTD Coarse Sand	Poorly Graded Sand (SP) Cu=4.44 Cc=0.62		NP		
3	New Orleans Filter Sand	Poorly Graded Sand (SP) Cu=2.09 Cc=0.95		NP		
4	Holland LZ Sand	Silty Sand (SM)		NP		
5	Tyndall AFB Sand	Poorly Graded Sand (SP) Cu=1.44 Cc=0.98		NP		
6	Yuma Sand	Poorly Graded Silty Sand (SP-SM) Cu=1.63 Cc=1.16		NP		

GRADATION CURVES	
PROJECT	**Fiber Stabilization**
SOURCE	Waterways Experiment Station
DATE	March 12, 1997

Figure 1. Gradation curves for tested sands

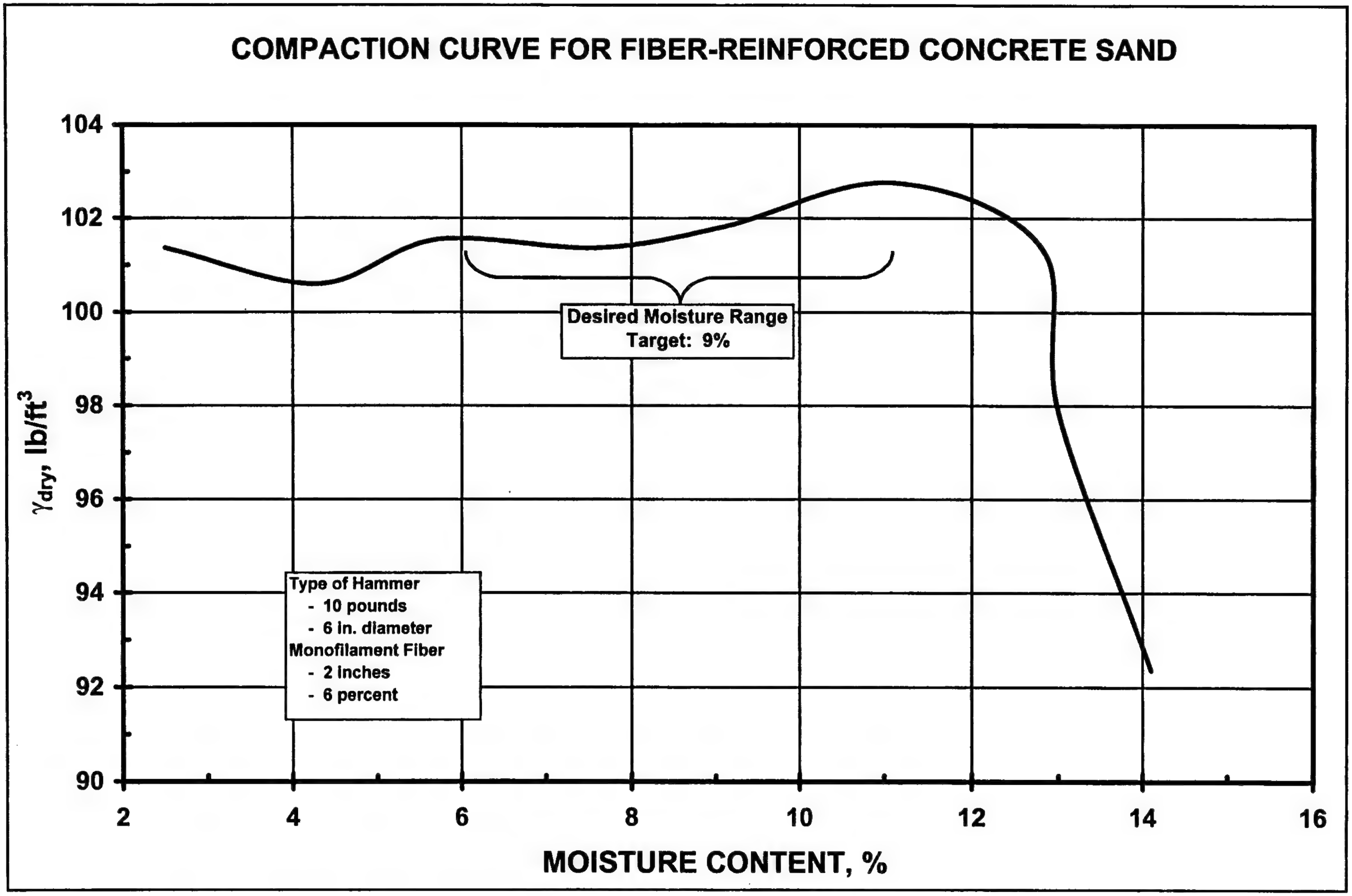


Figure 2. Effect of moisture content on density of concrete sand

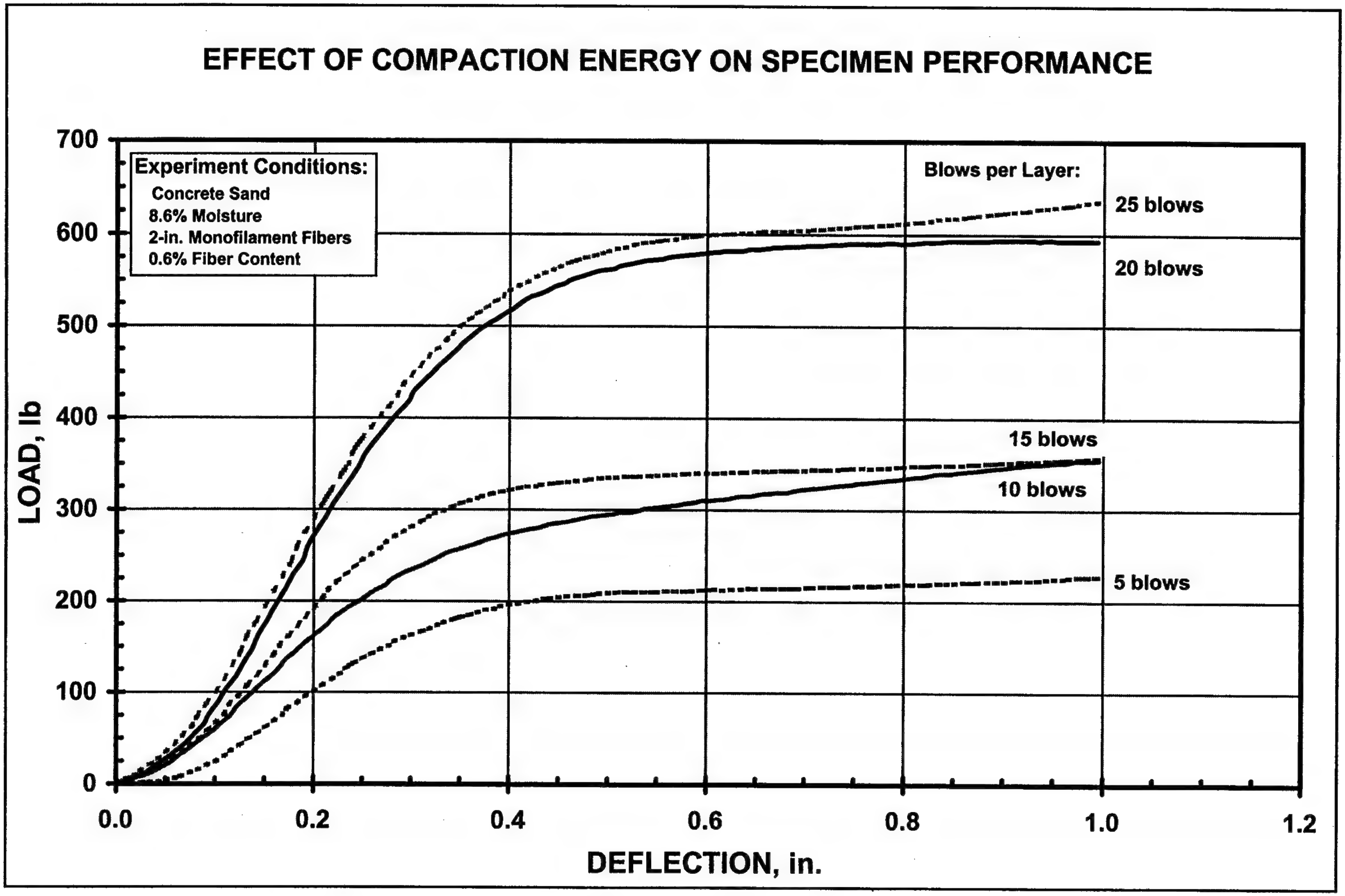


Figure 3. Unconfined compression test results at varying compaction efforts

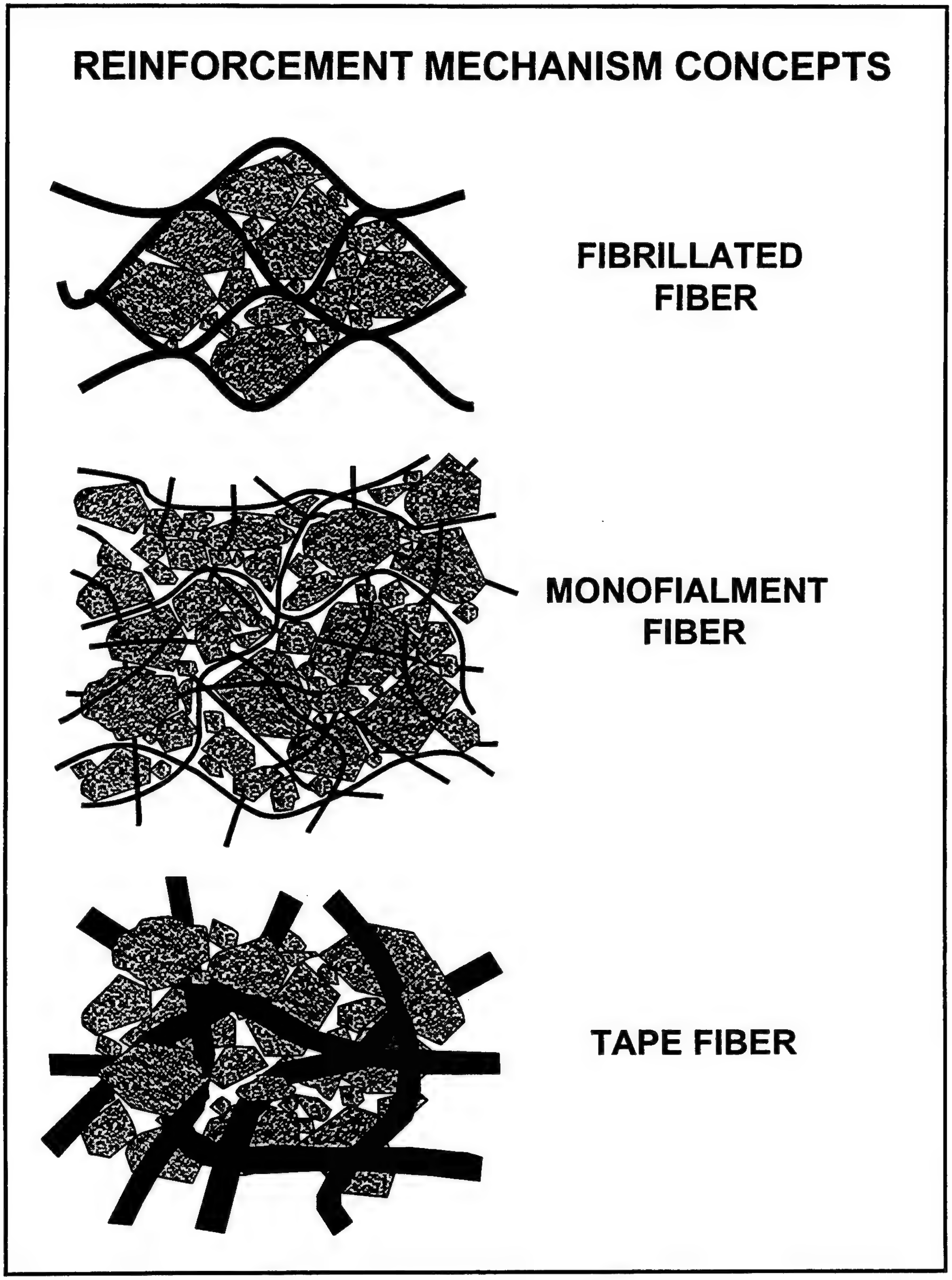


Figure 4. Illustration of fiber reinforcement

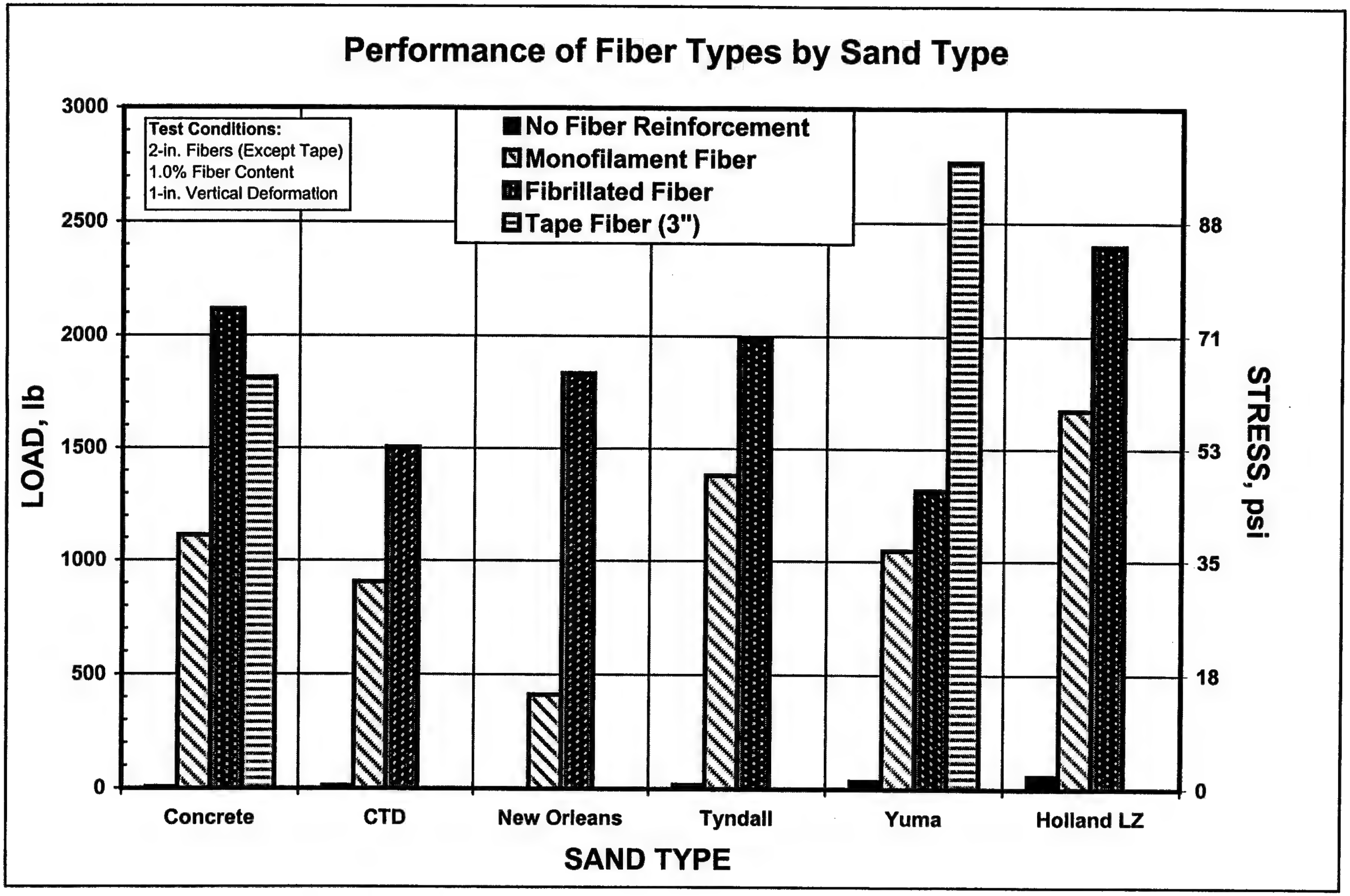


Figure 5. Performance of fiber types in different sands

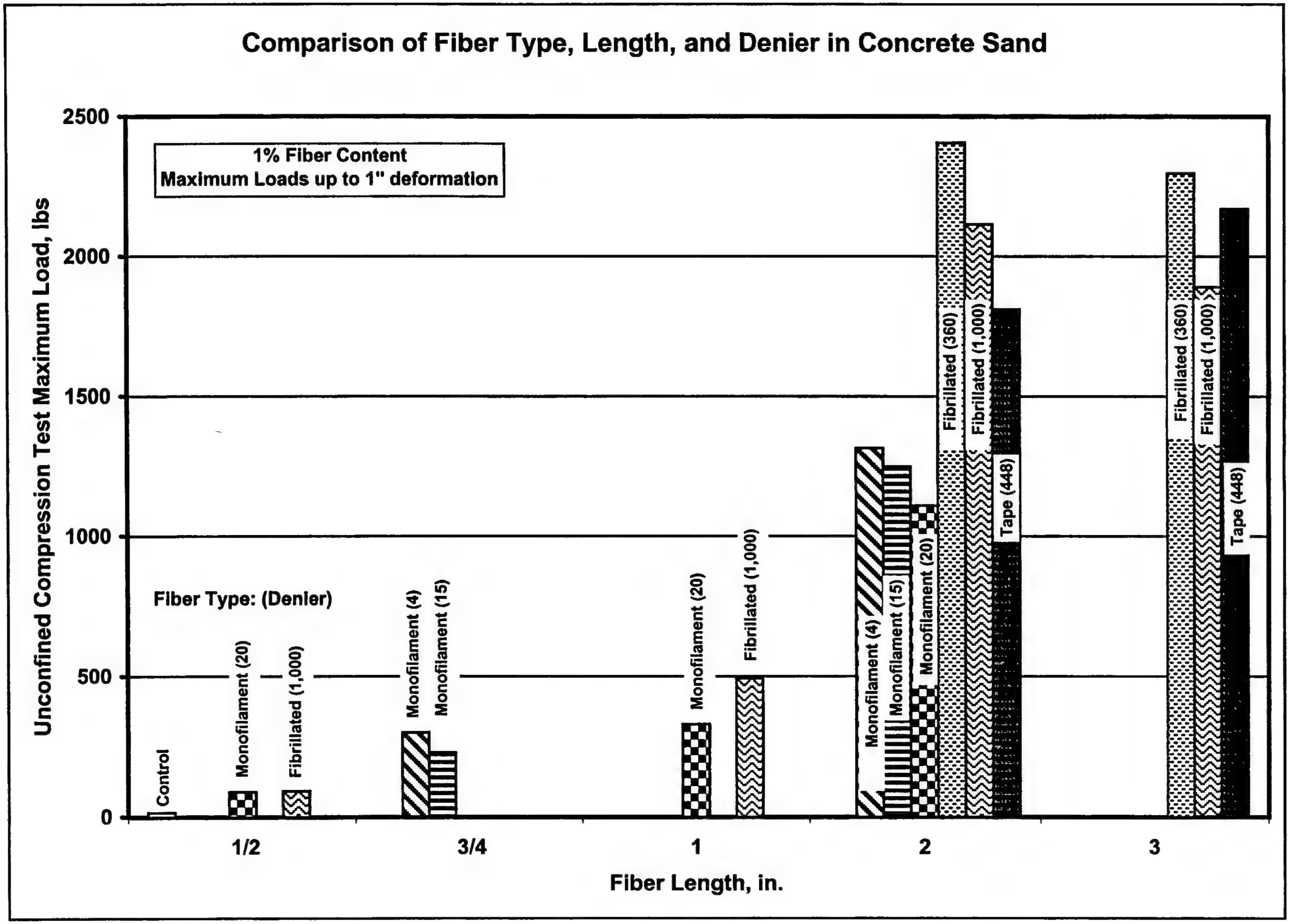


Figure 6. Comparison of fiber type, length, and denier in concrete sand

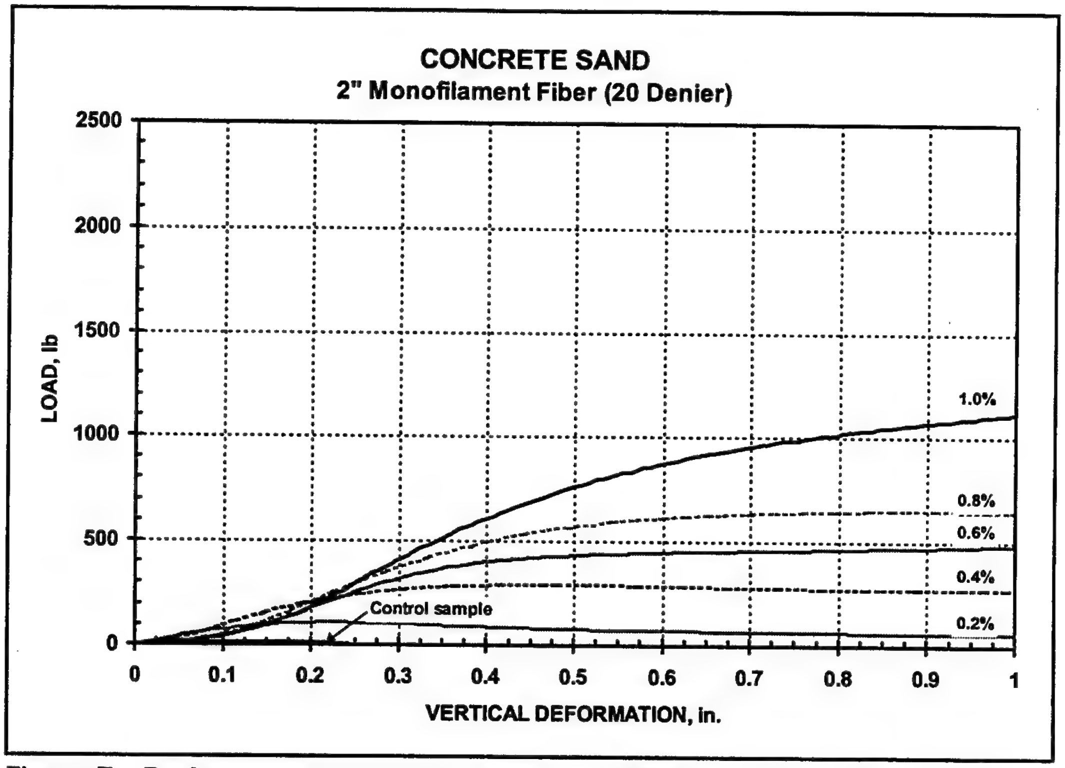


Figure 7. Performance of 2-in. monofilament (20 denier) fibers in concrete sand

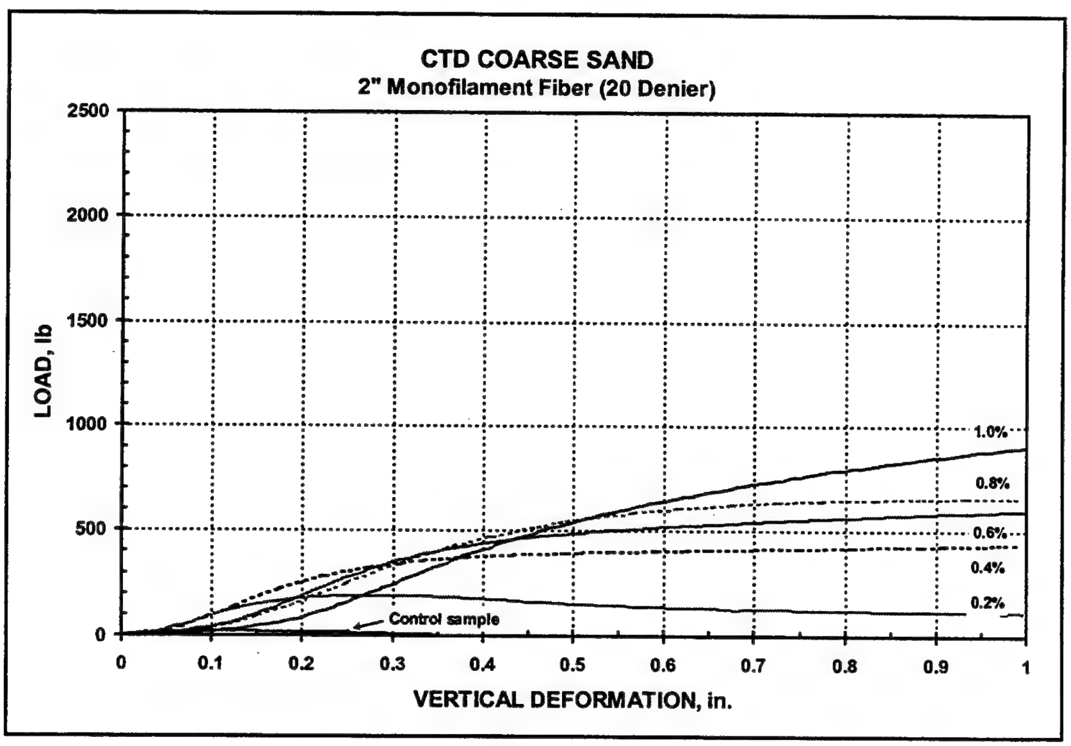


Figure 8. Performance of 2-in. monofilament (20 denier) fibers in CTD coarse sand

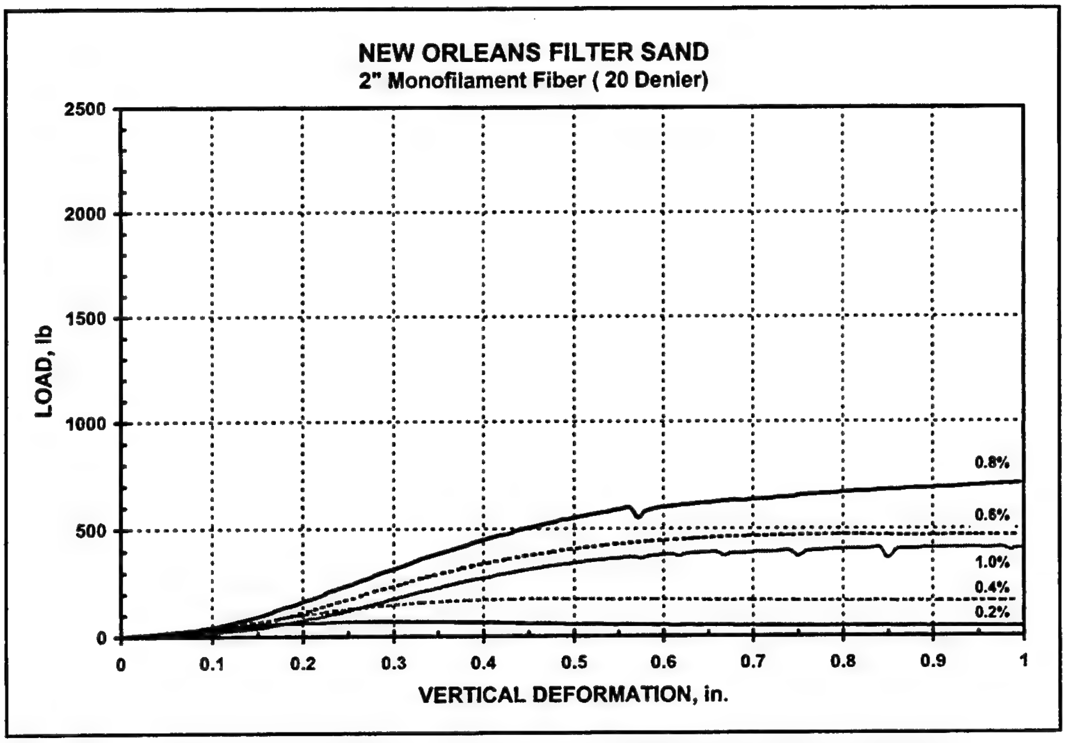


Figure 9. Performance of 2-in. monofilament (20 denier) fibers in New Orleans filter sand

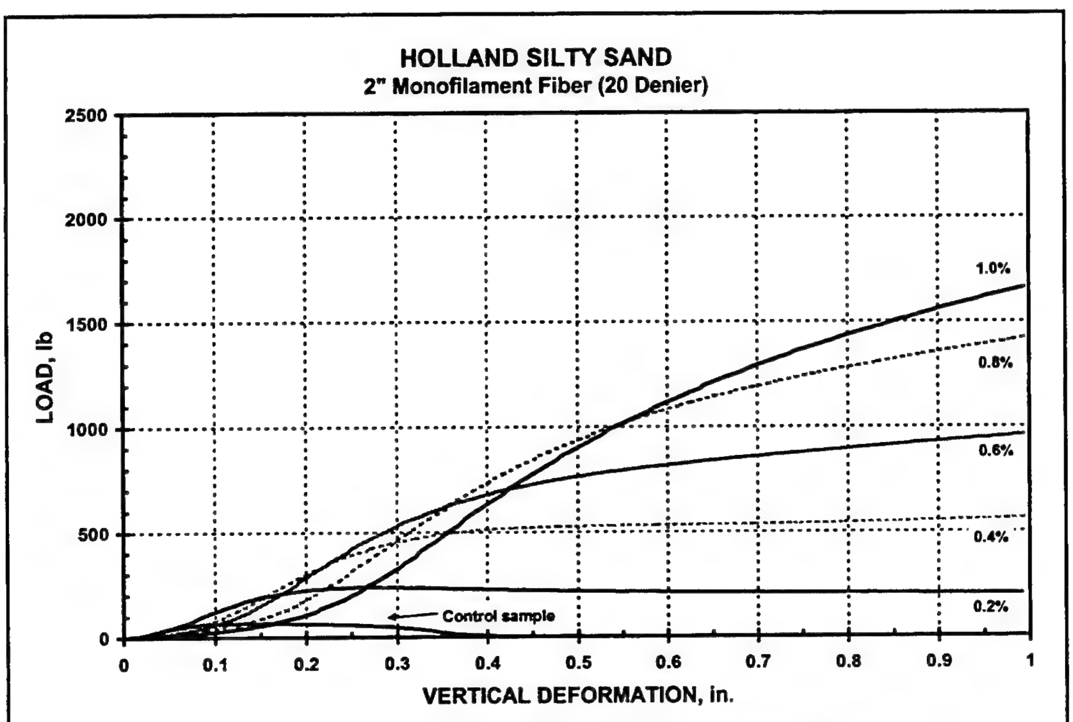


Figure 10. Performance of 2-in. monofilament (20 denier) fibers in Holland LZ sand

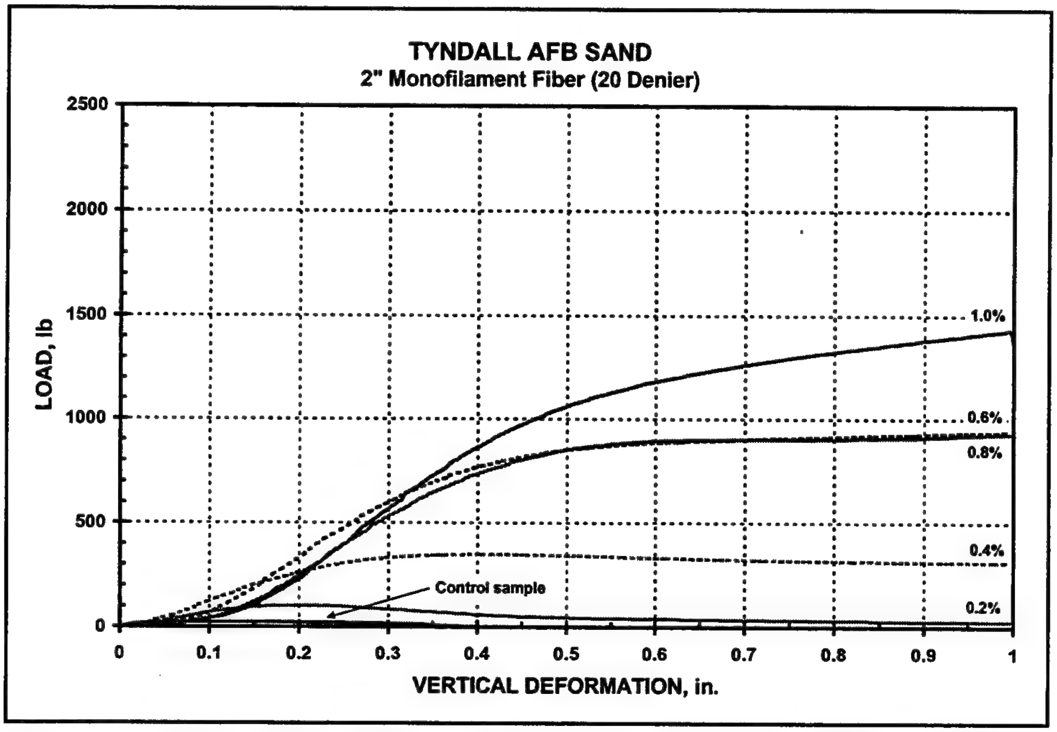


Figure 11. Performance of 2-in. monofilament (20 denier) fibers in Tyndall AFB sand

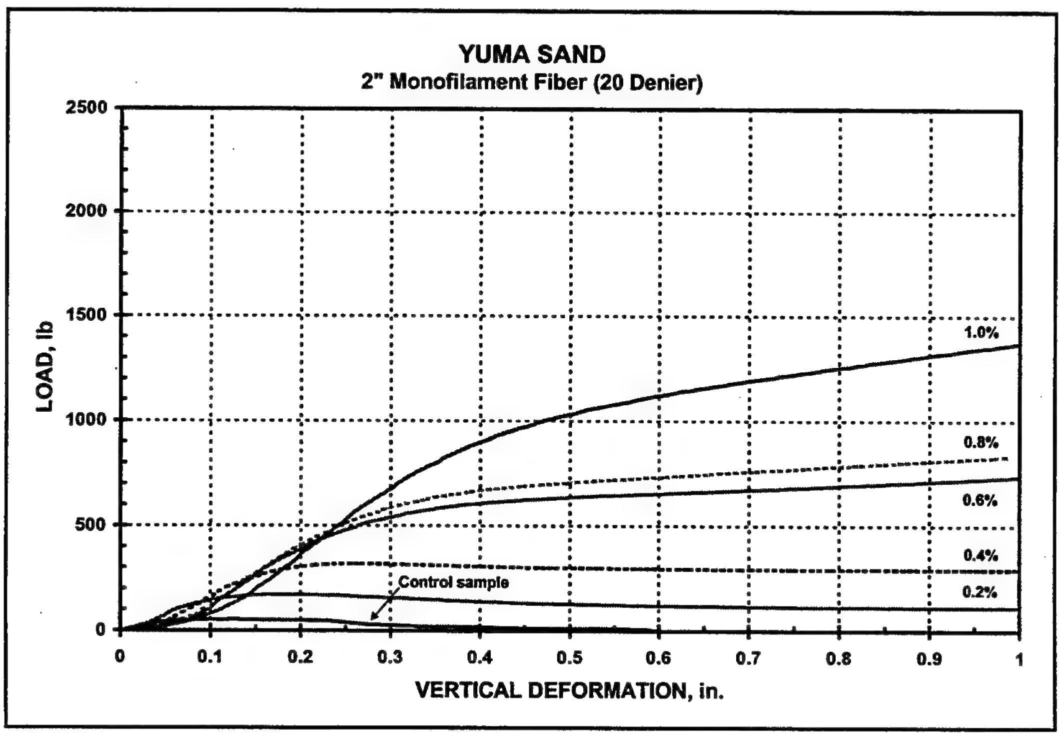


Figure 12. Performance of 2-in. monofilament (20 denier) fibers in Yuma sand

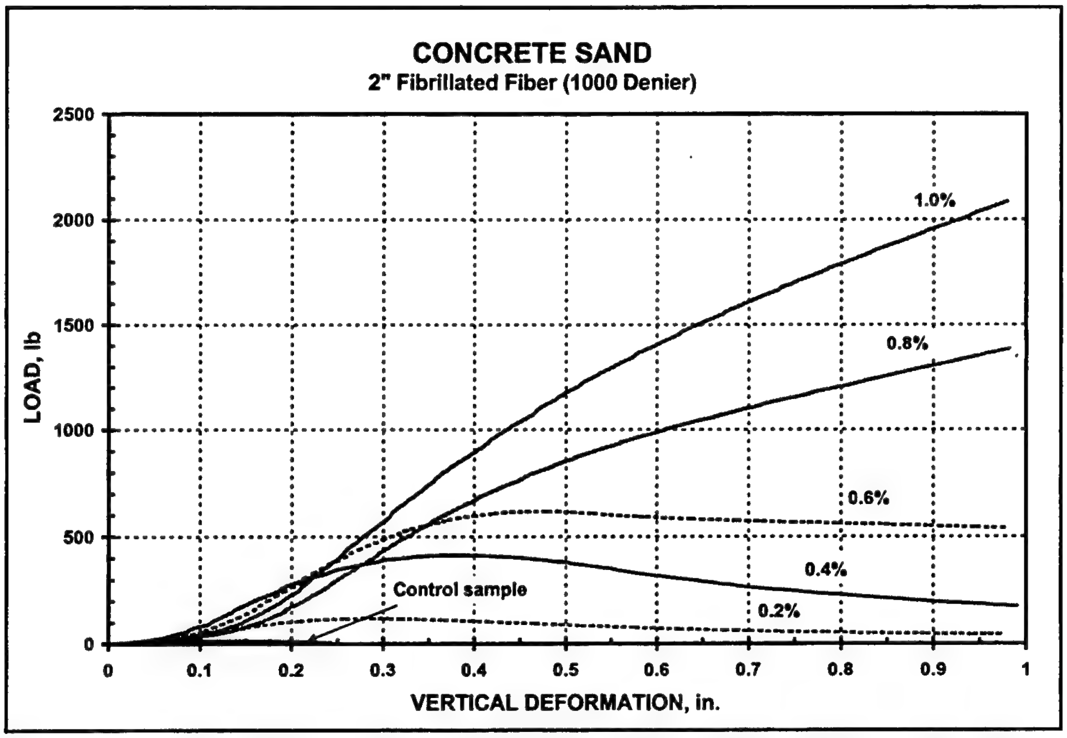


Figure 13. Performance of 2-in. fibrillated (1,000 denier) fibers in concrete sand

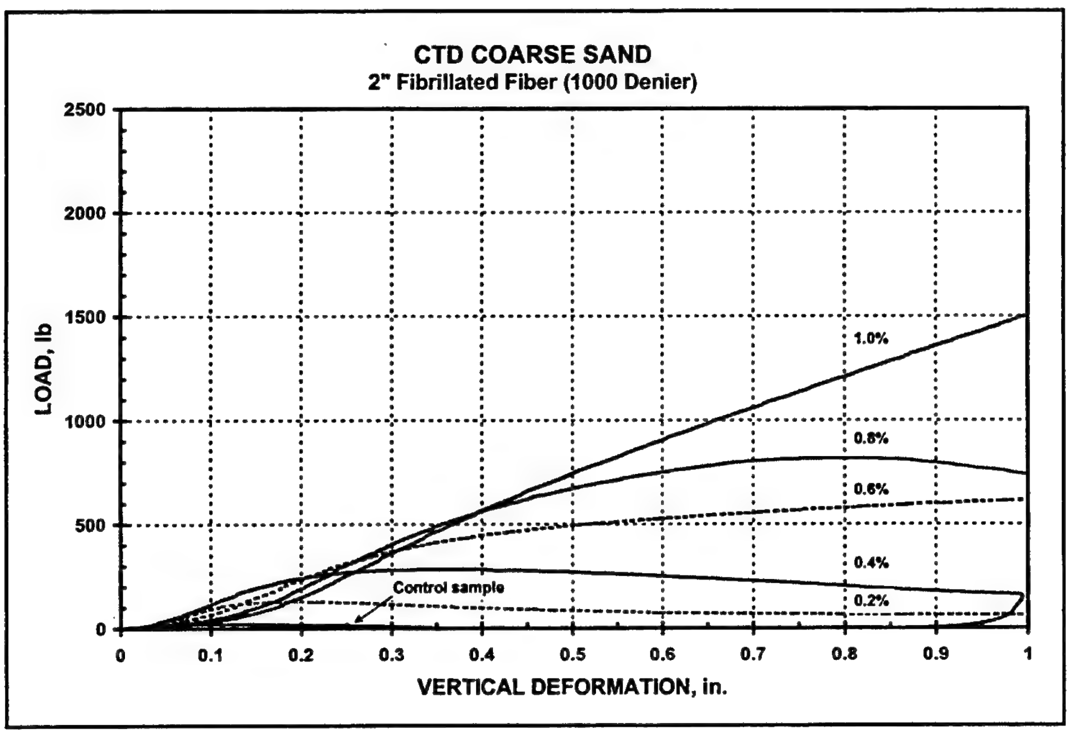


Figure 14. Performance of 2-in. fibrillated (1,000 denier) fibers in CTD coarse sand

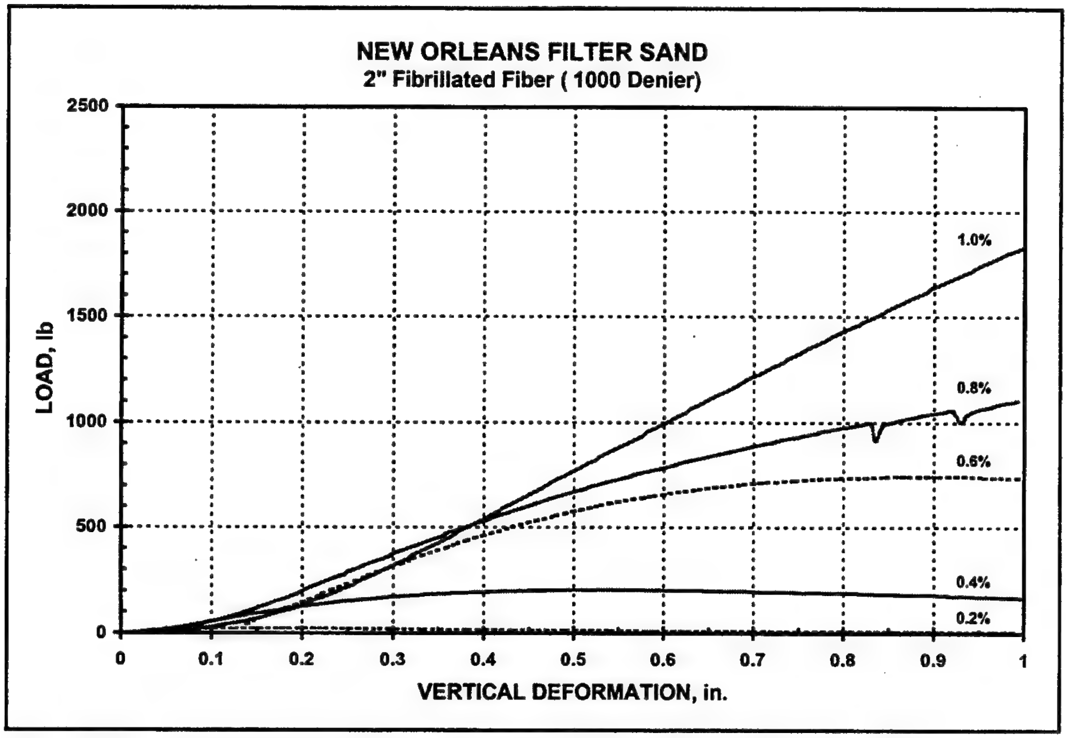


Figure15. Performance of 2-in. fibrillated (1,000 denier) fibers in New Orleans filter sand

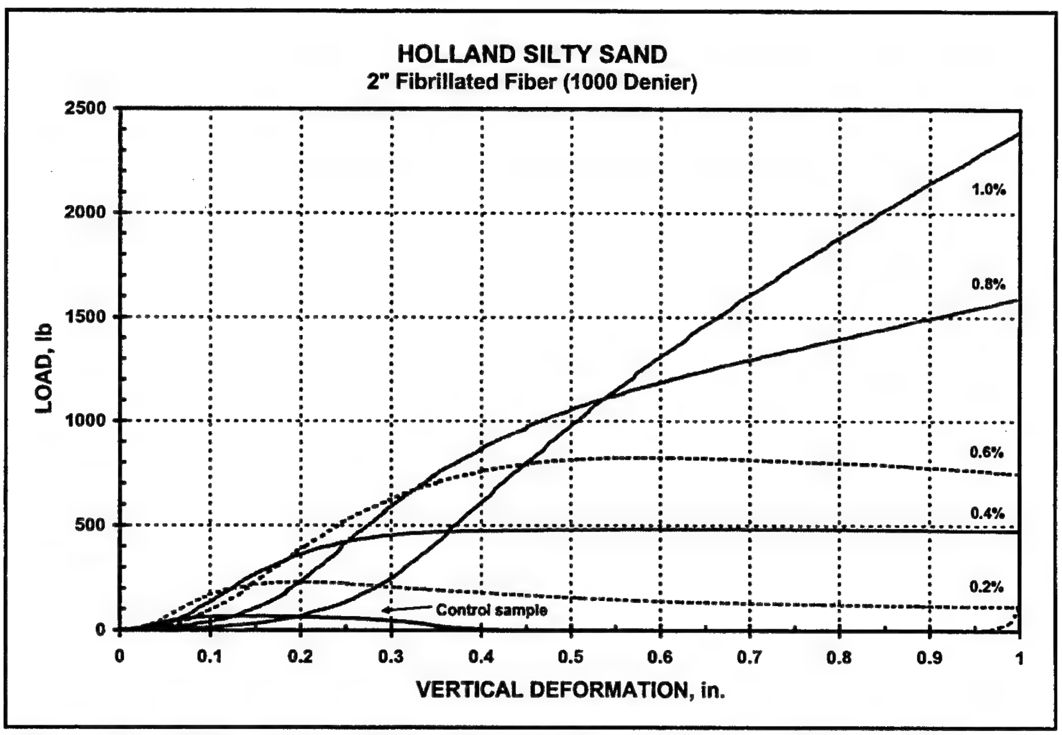


Figure 16. Performance of 2-in. fibrillated (1,000 denier) fibers in Holland LZ sand

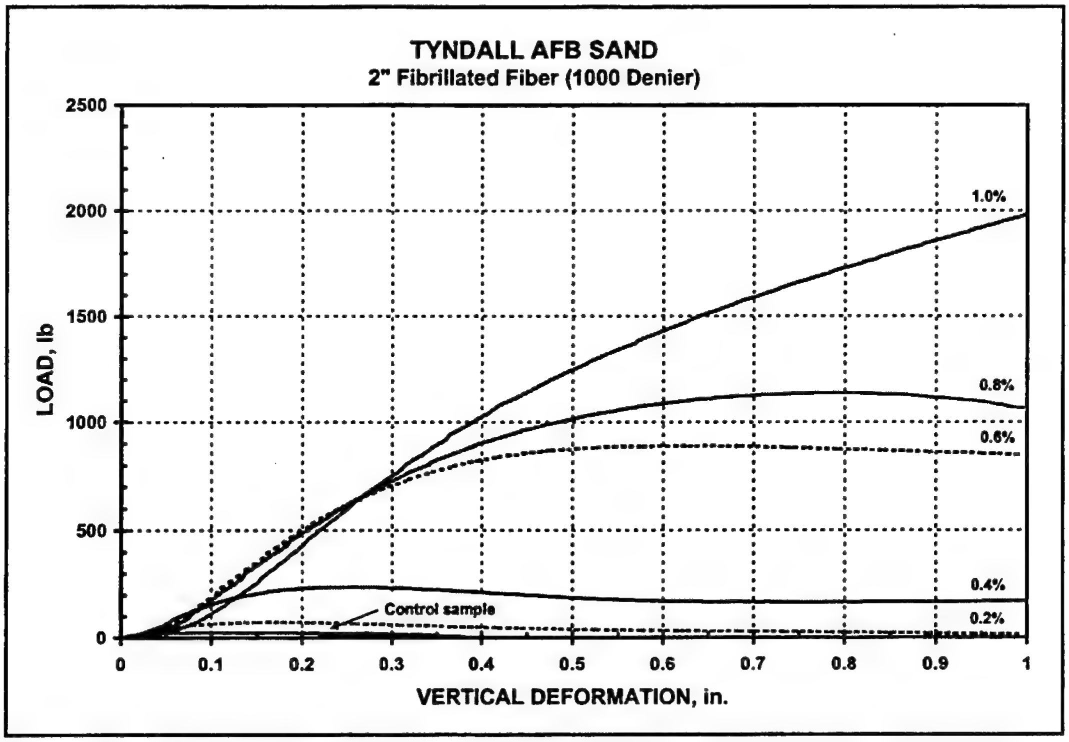


Figure 17. Performance of 2-in. fibrillated (1,000 denier) fibers in Tyndall AFB sand

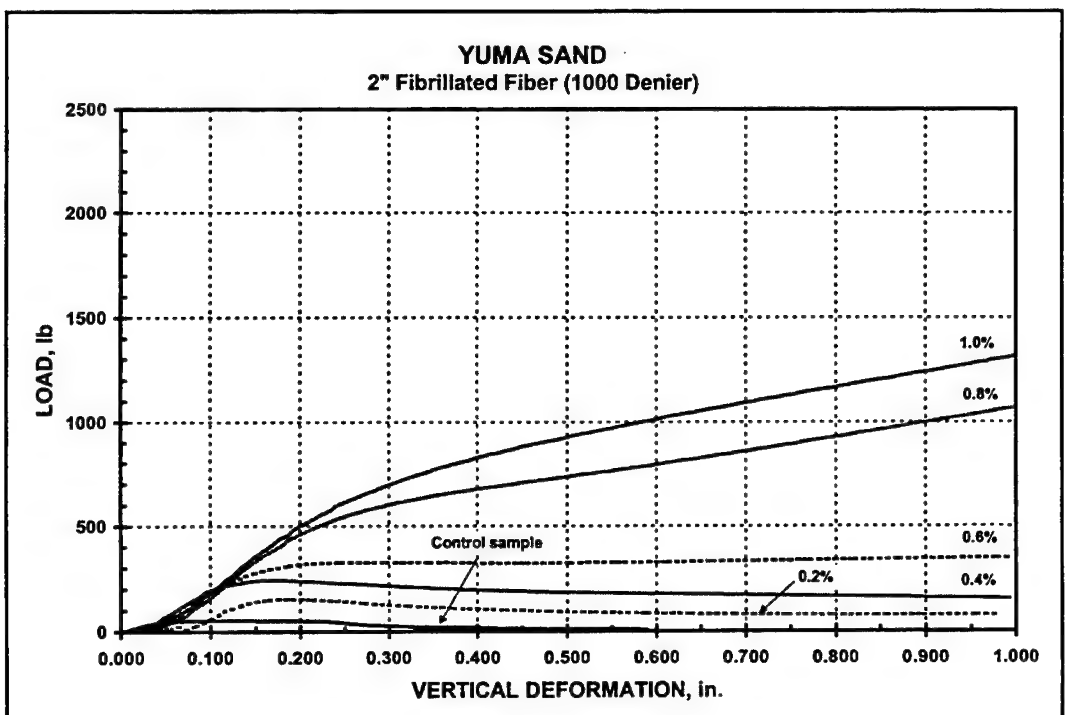


Figure 18. Performance of 2-in. fibrillated (1,000 denier) fibers in Yuma sand

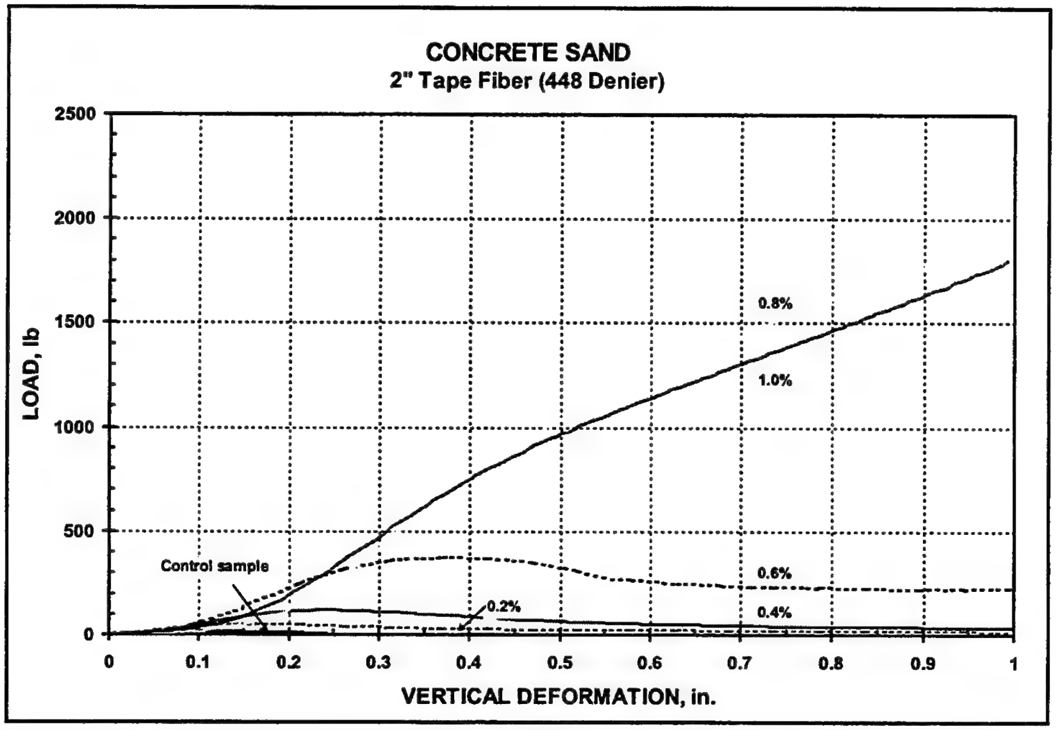


Figure 19. Performance of 2-in. tape (448 denier) fibers in concrete sand

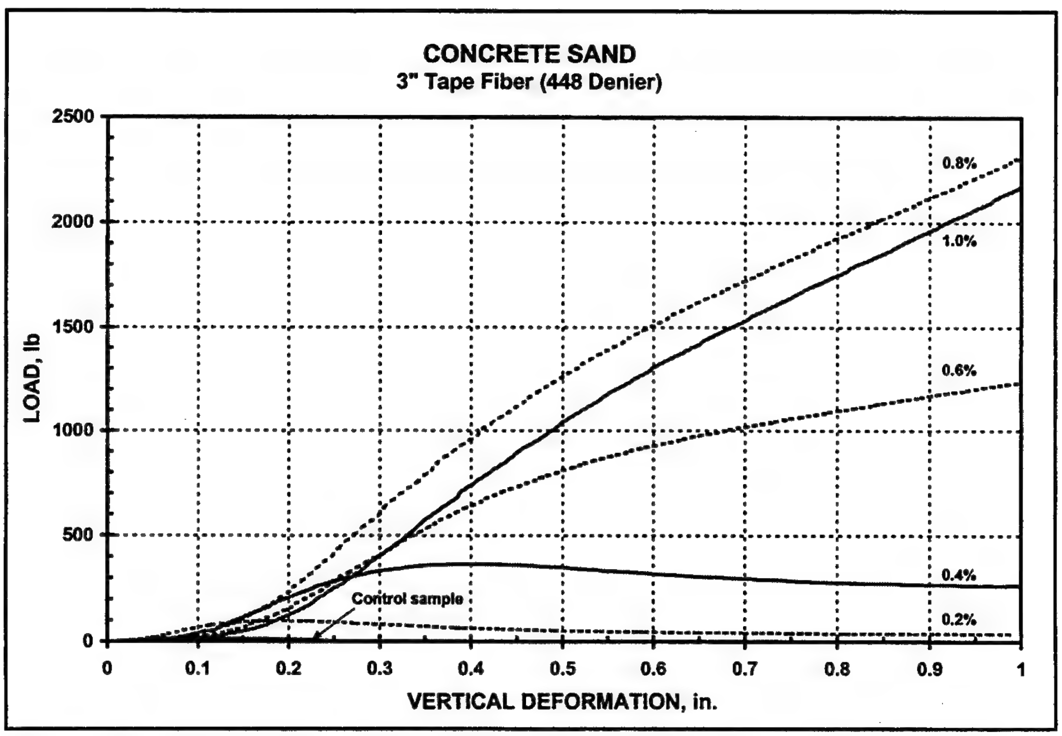


Figure 20. Performance of 3-in. tape (448 denier) fibers in concrete sand

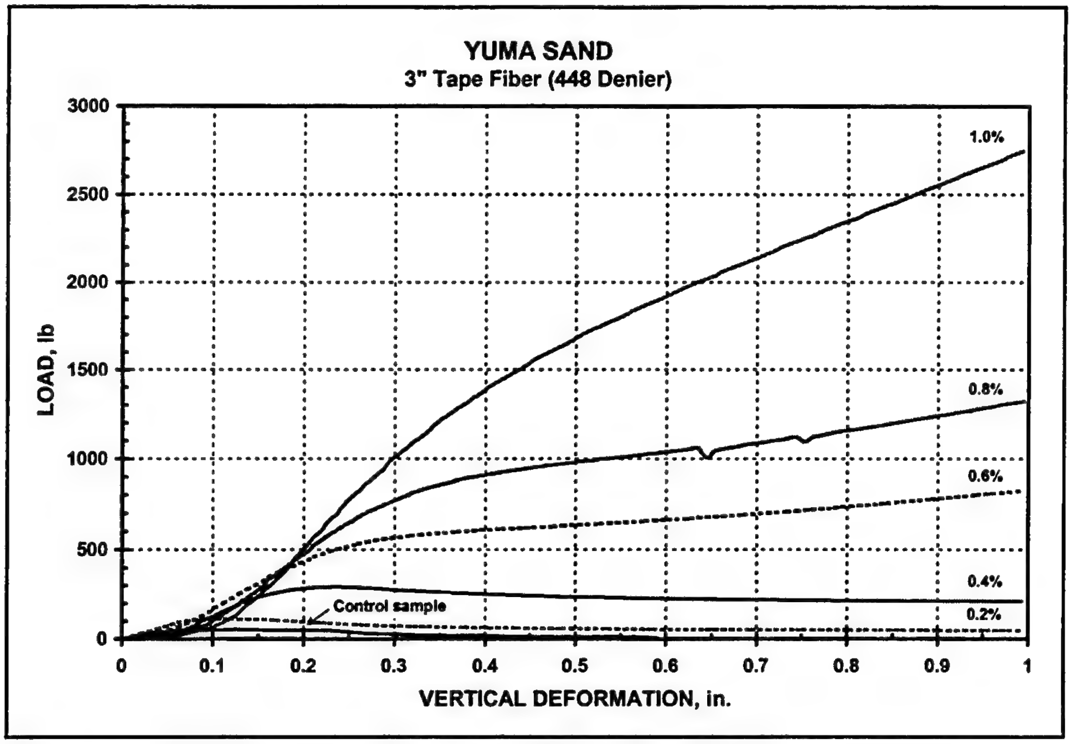


Figure 21. Performance of 3-in. tape (448 denier) fibers in Yuma sand

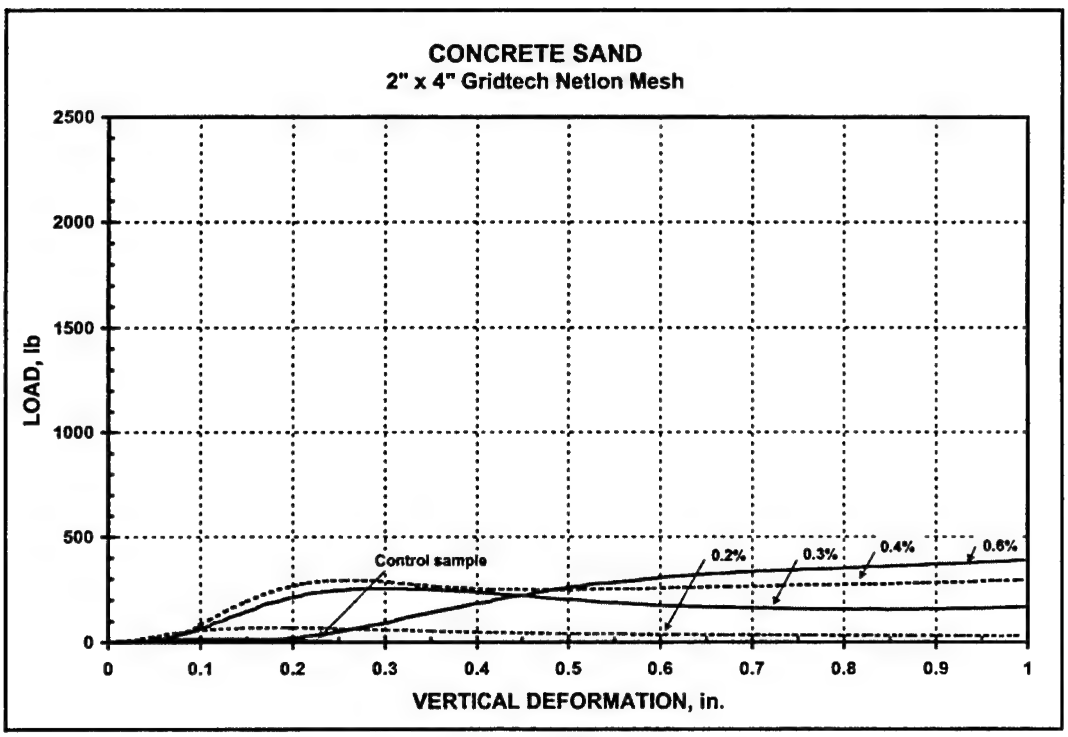


Figure 22. Performance of Netlon mesh fiber elements in concrete sand

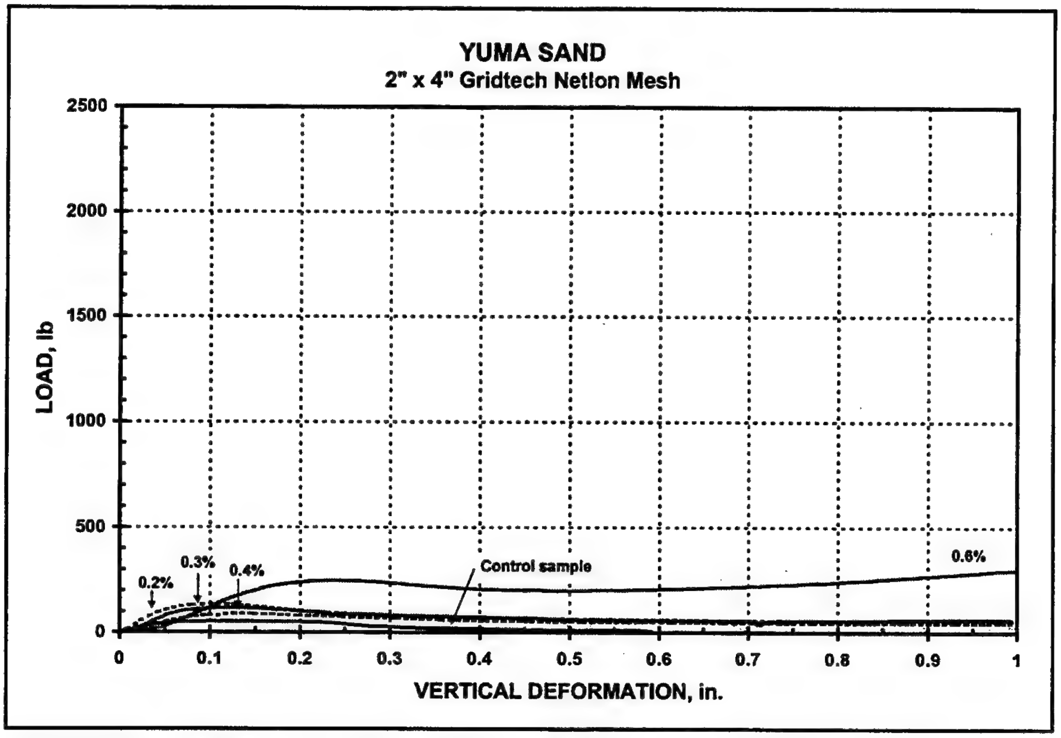


Figure 23. Performance of Netlon mesh fiber elements in Yuma sand

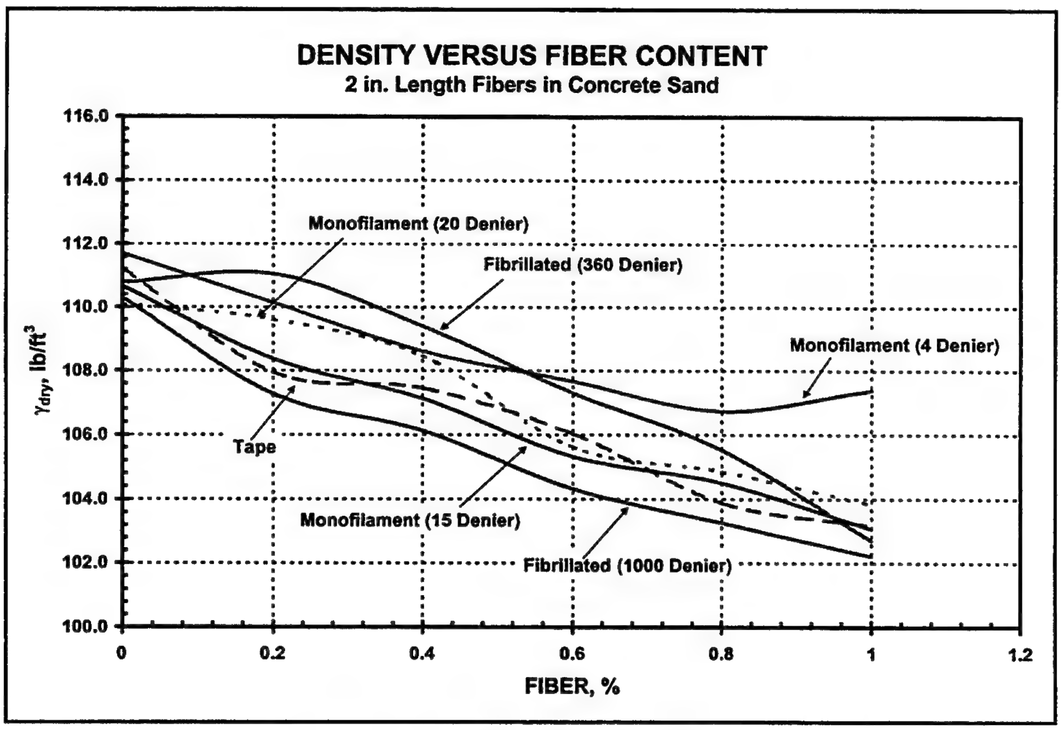


Figure 24. Typical decrease in sample density with increasing fiber content

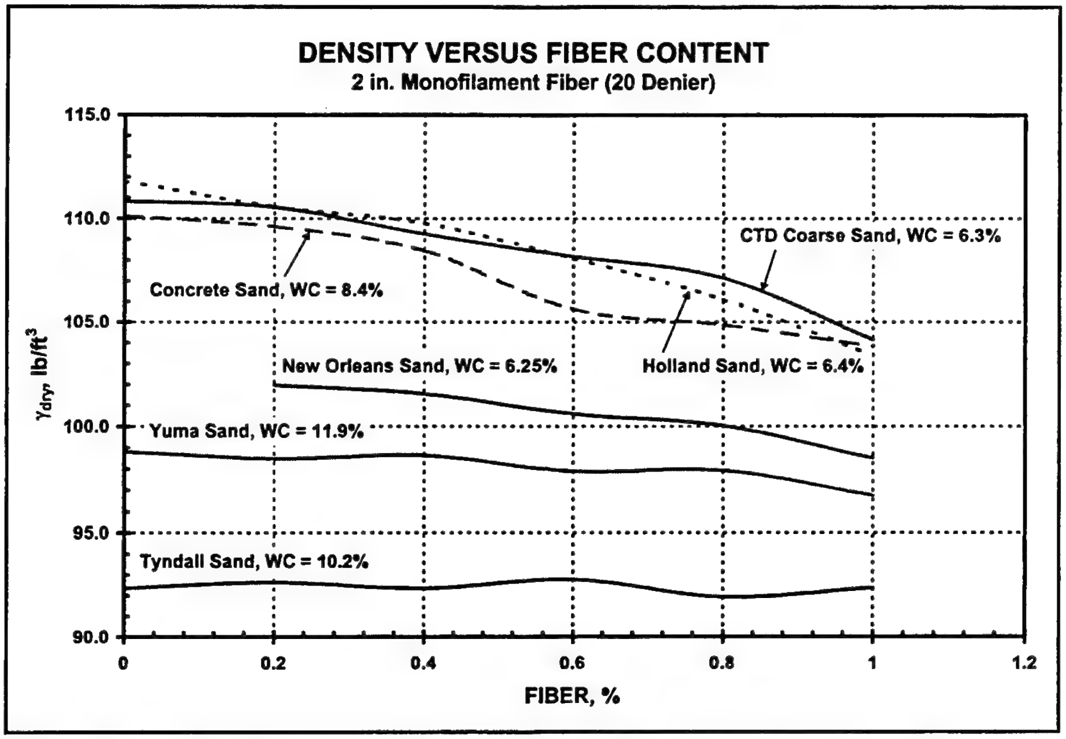


Figure 25. Typical decrease in sample density in different sands with increasing fiber content

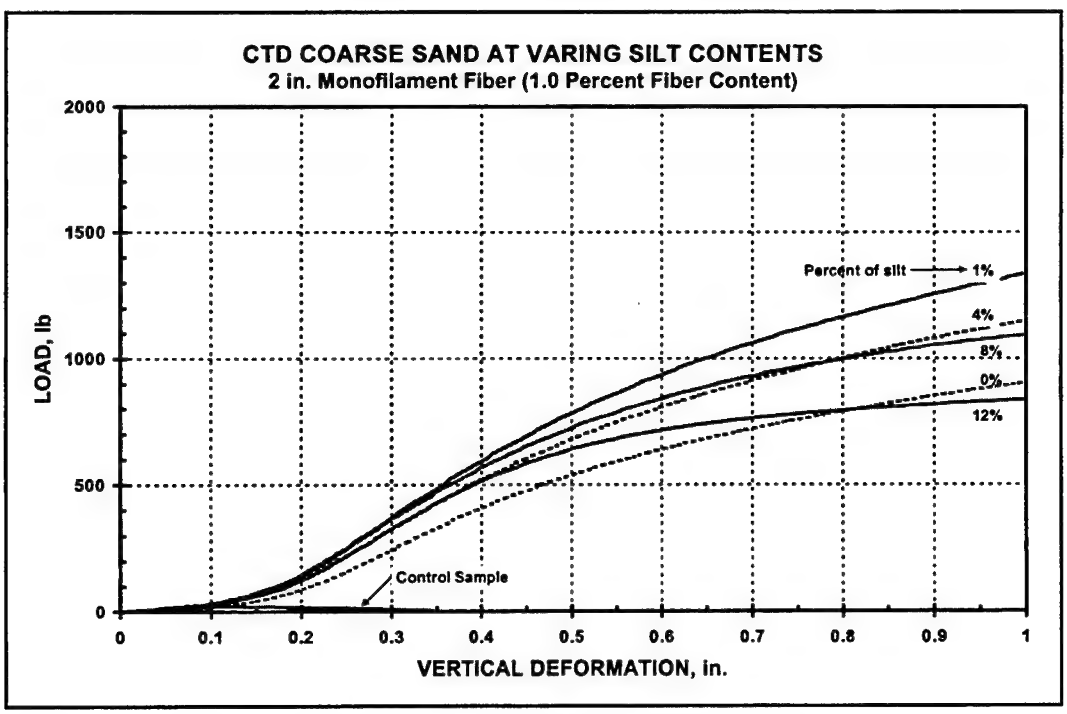


Figure 26. Effect of silt content on specimen performance

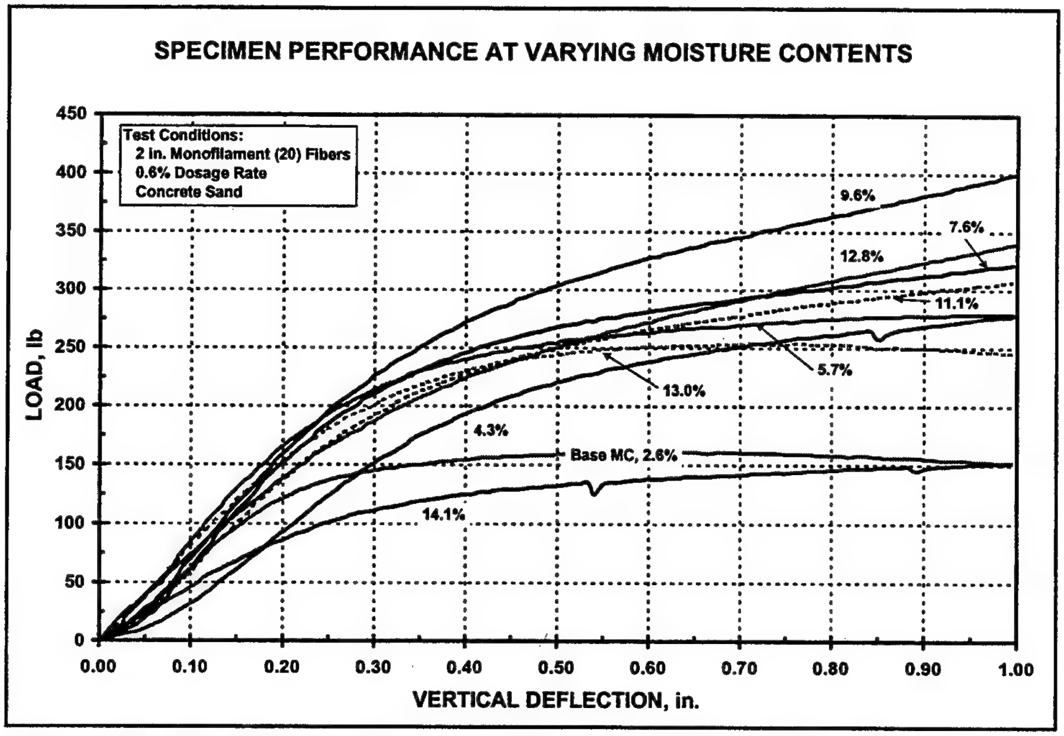


Figure 27. Influence of moisture content on specimen performance

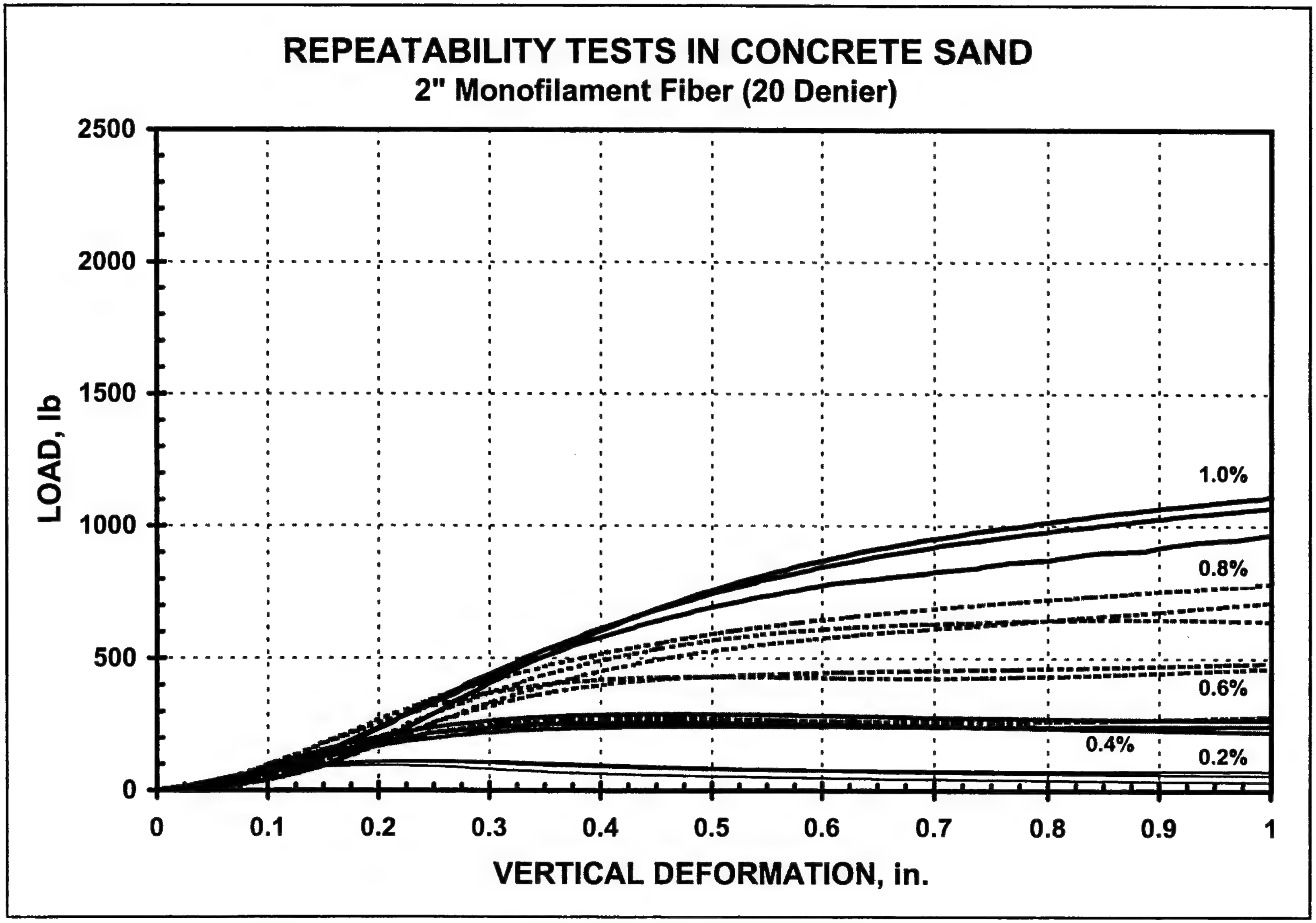


Figure 28. Repeatability tests for 2-in. monofilament (20 denier) fibers in concrete sand

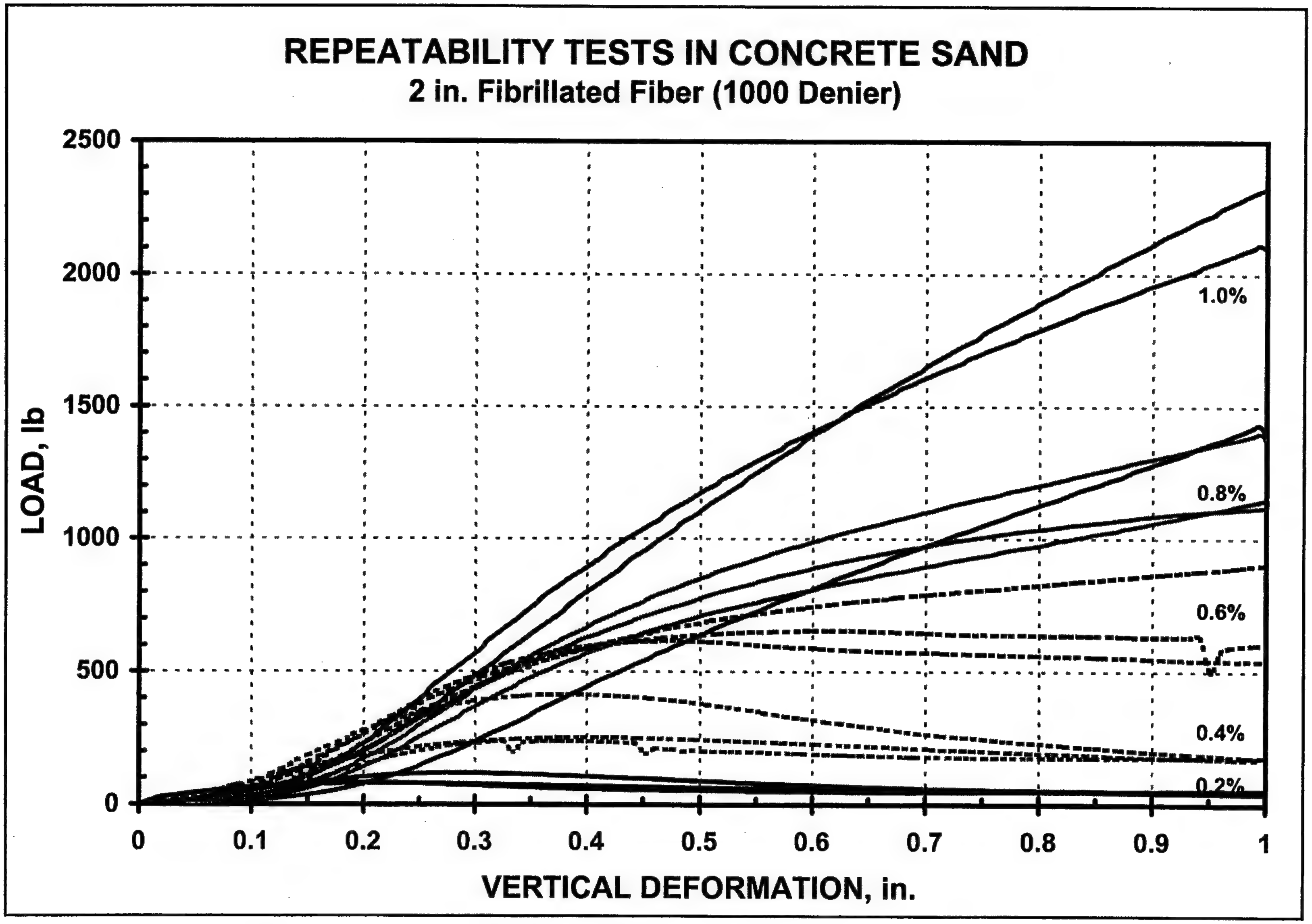


Figure 29. Repeatability tests for 2-in. fibrillated (1,000 denier) fibers in concrete sand

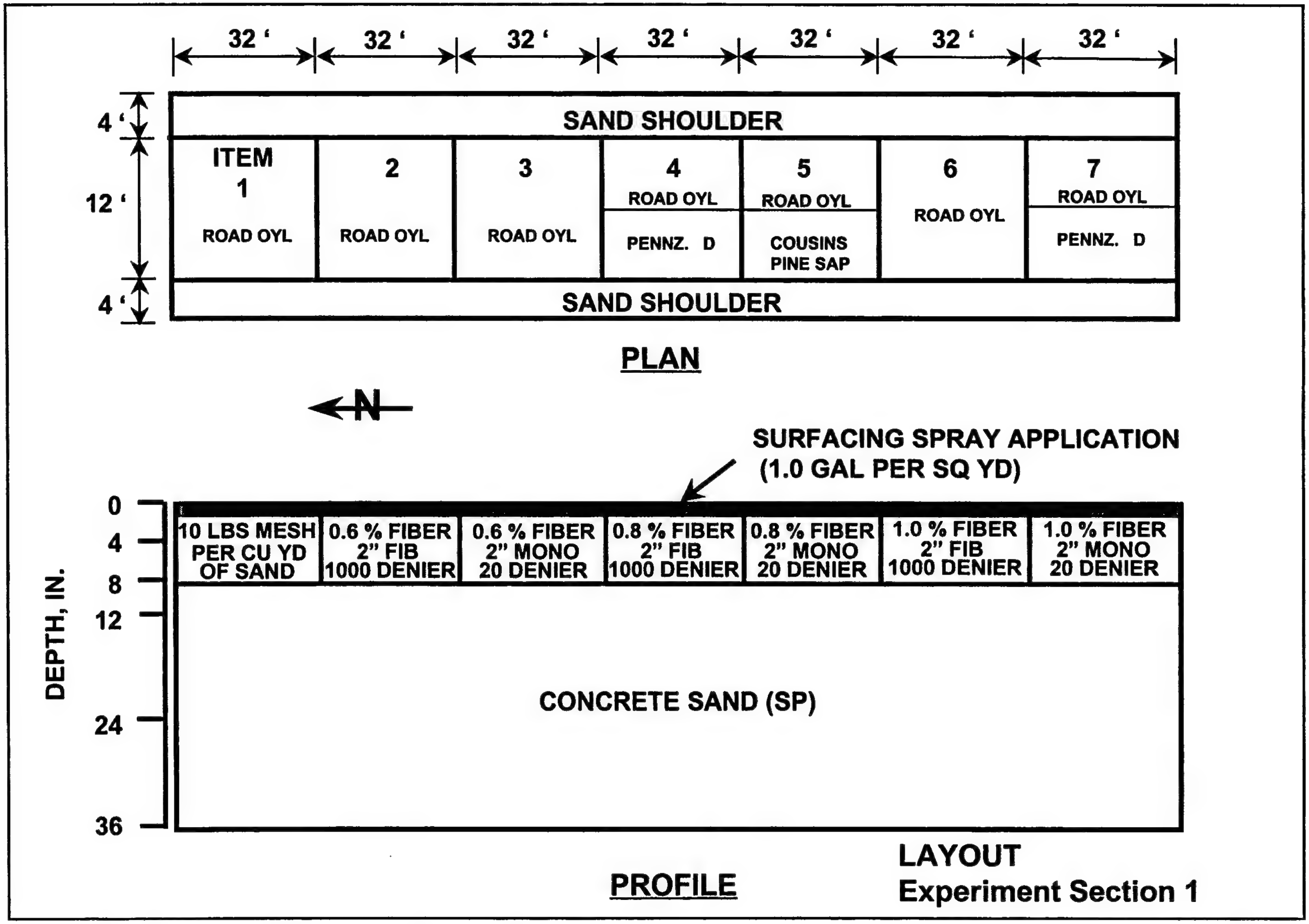


Figure 30. Plan and profile of experiment section one

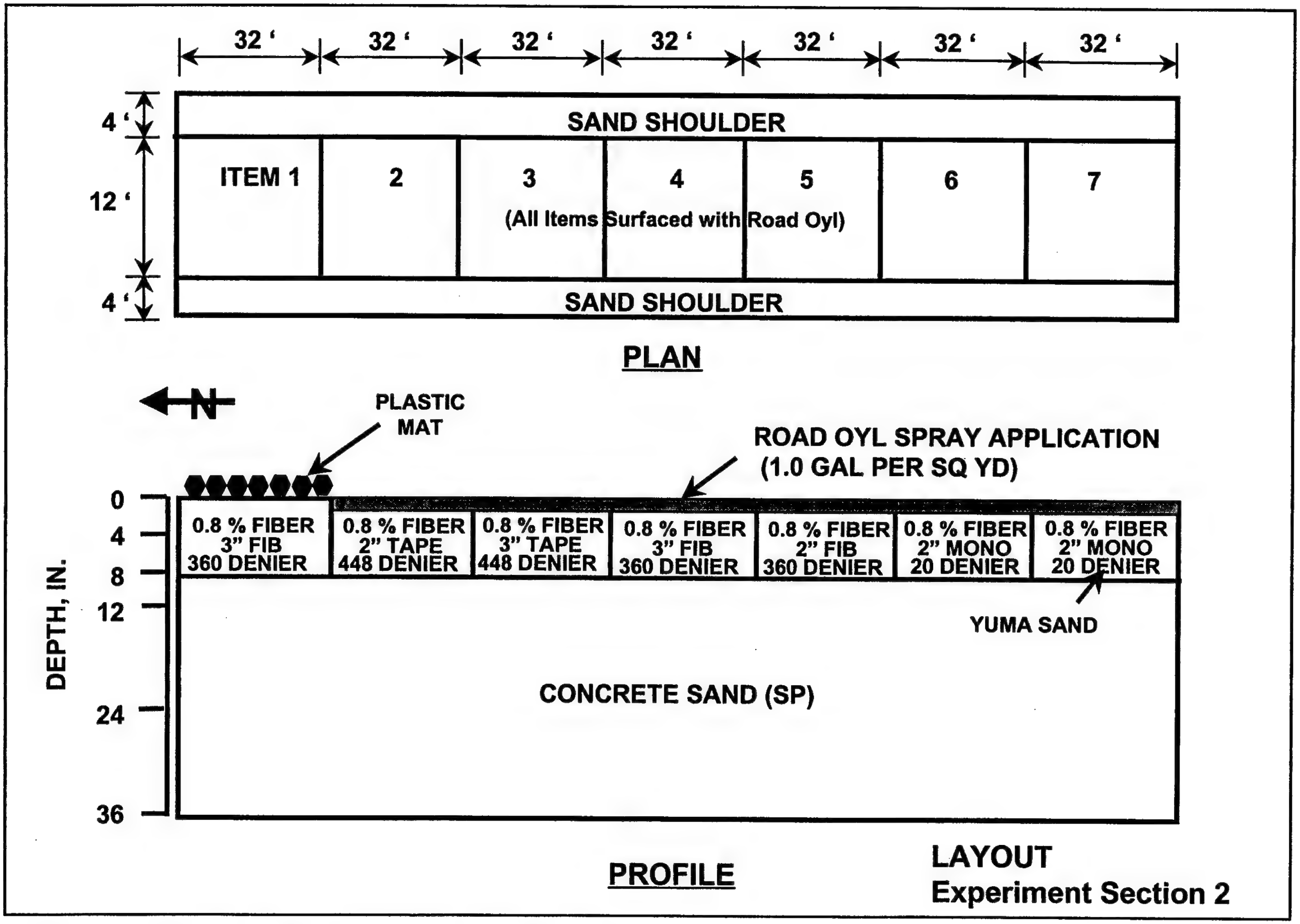


Figure 31. Plan and profile of experiment section two

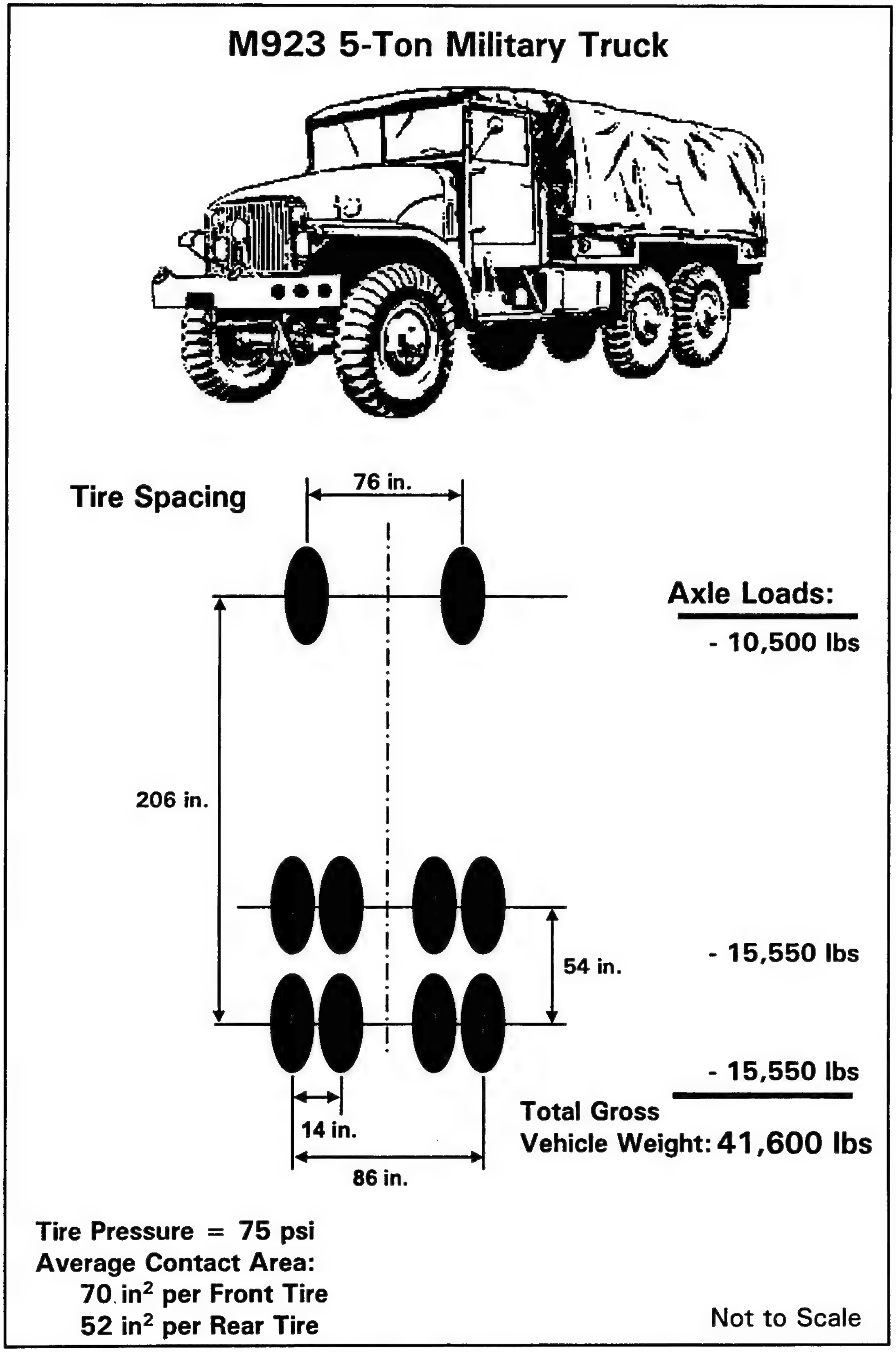


Figure 32. Test vehicle load conditions

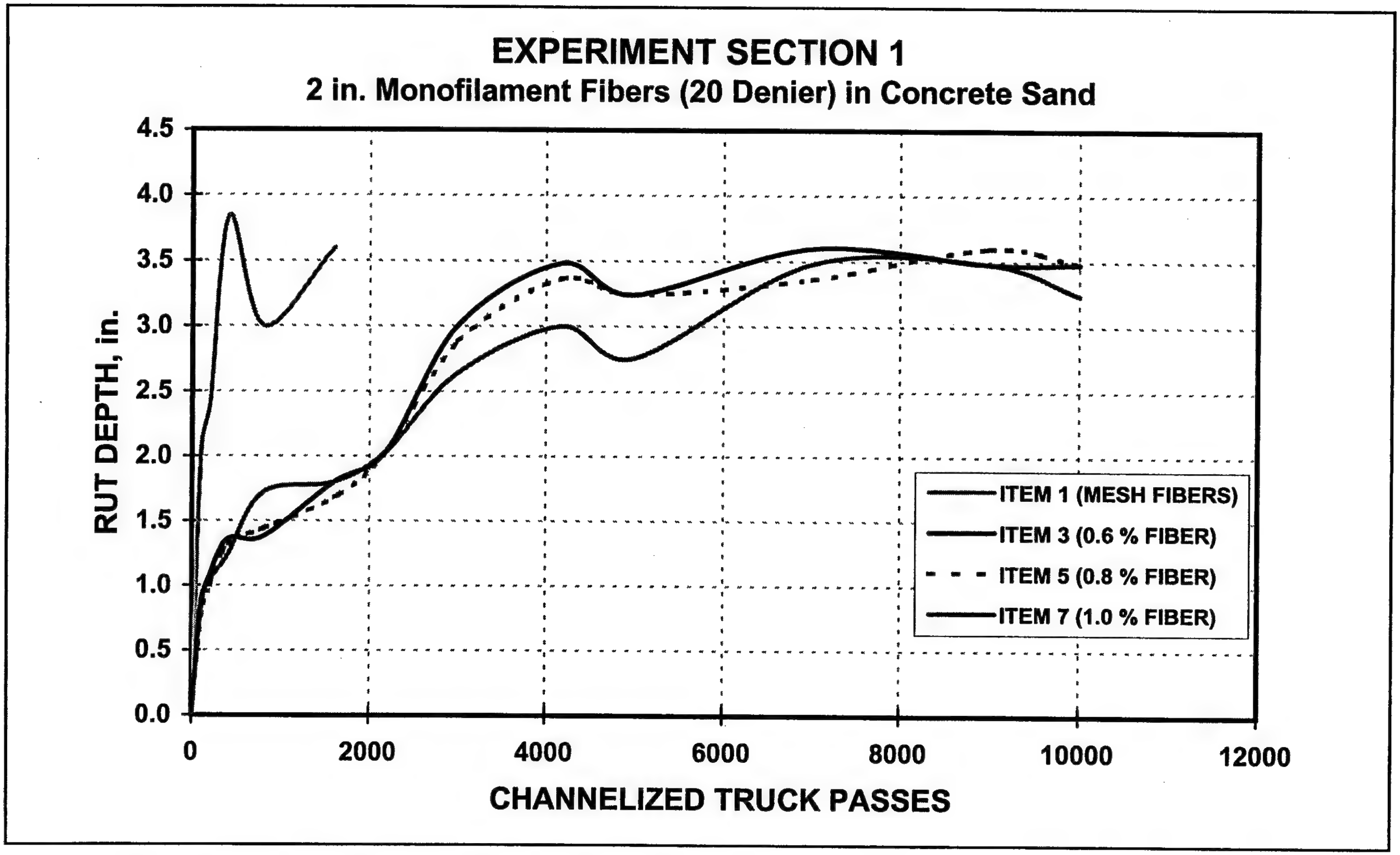


Figure 33. Rut depth measurements for the monofilament fiber items 1, 3, 5, and 7 of experiment section one

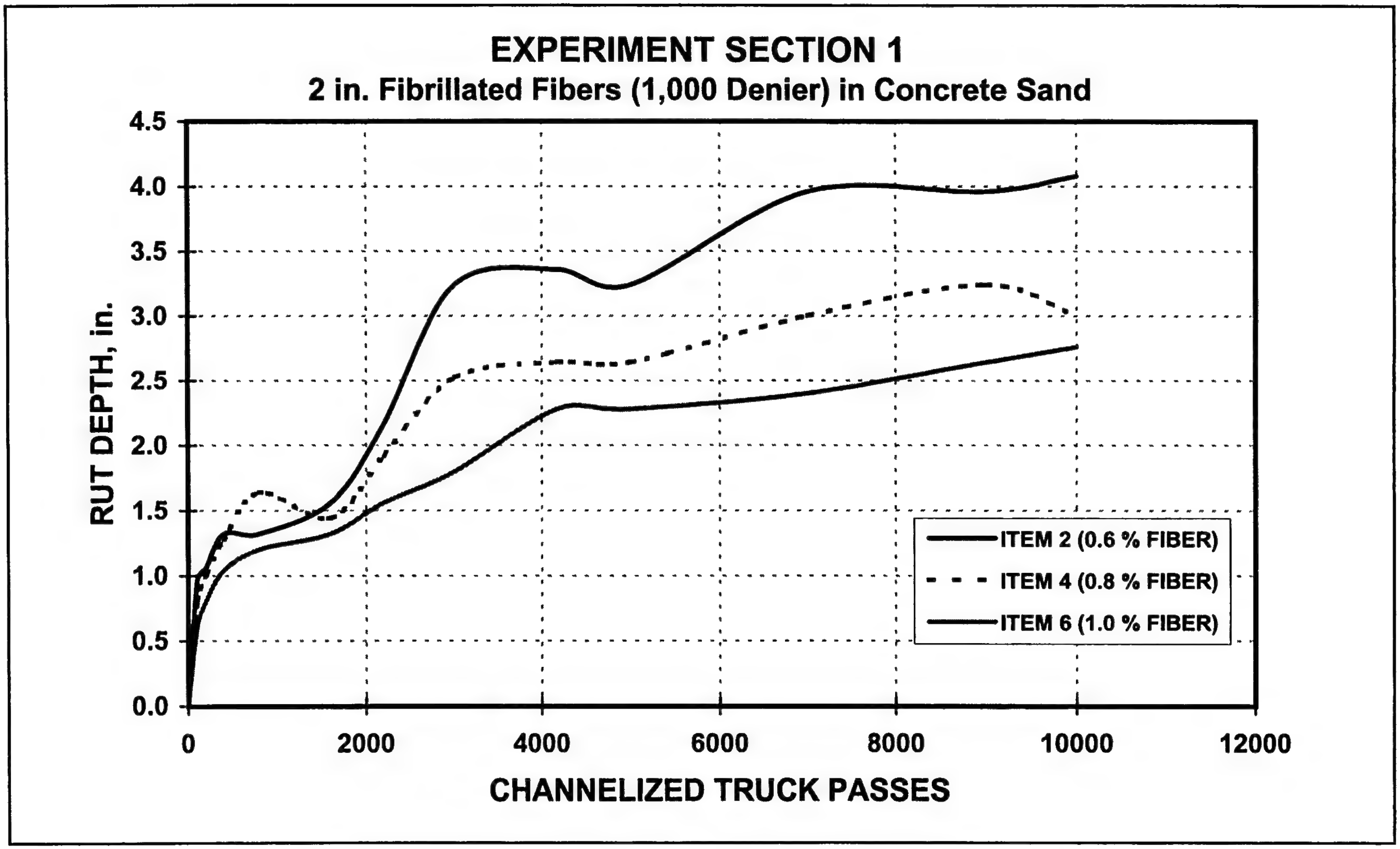


Figure 34. Rut depth measurements for the fibrillated fiber items 2, 4, and 6 of experiment section one

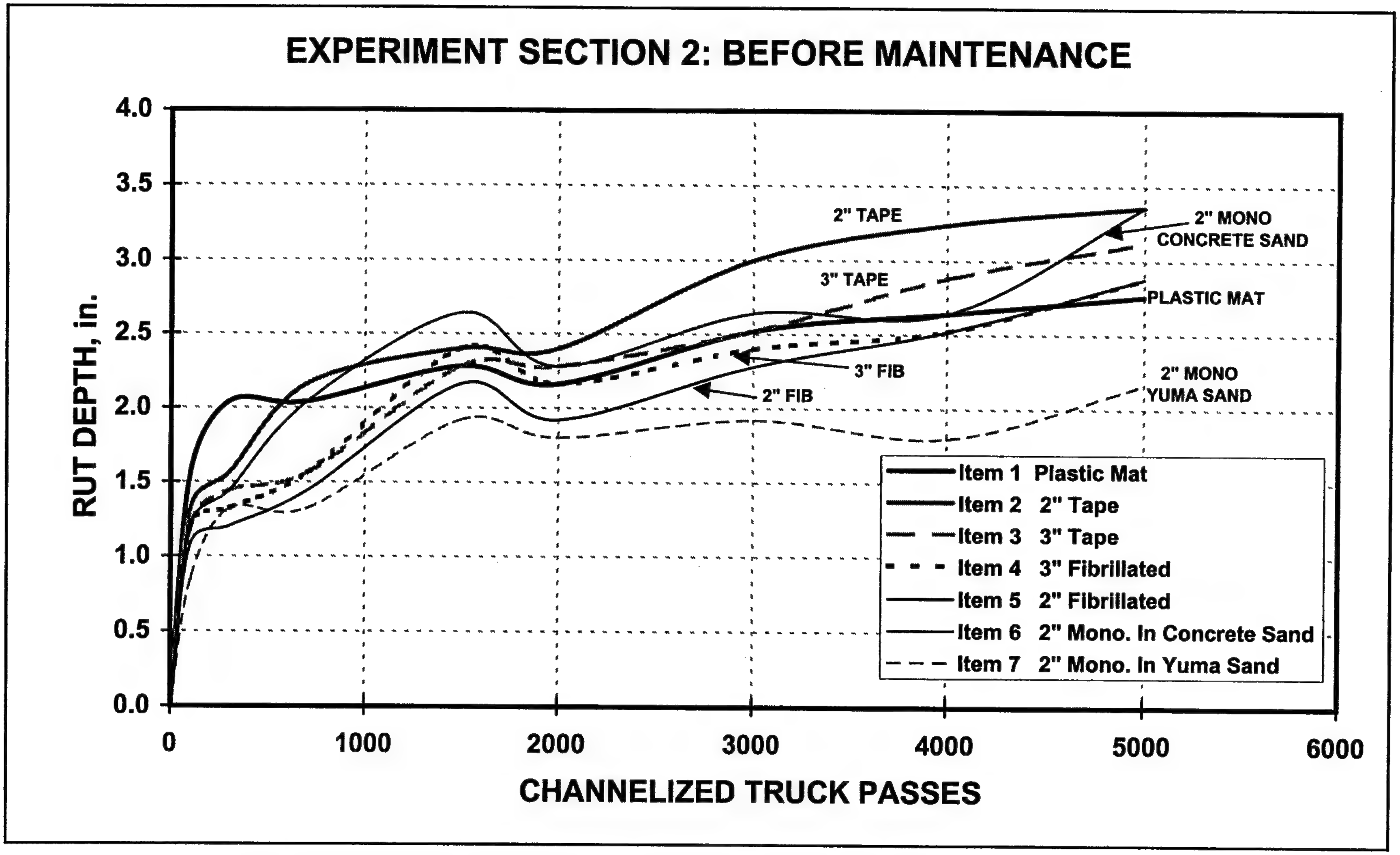


Figure 35. Rut depth measurements for all items of experiment section two before maintenance

DCP TEST DATA

File Name: DCP

Project: *Experiment Section 2*
Location: Sand Shoulder
Date: 27-Jun-98
Soil Type(s): SP SUBGRADE

Hammer
○ 10.1 lbs.
● 17.6 lbs.
○ Both hammers used

Soil Type
○ CH
○ CL
● All other soils

No. of Blows	Accumulative Penetration (mm)	Type of Hammer
0	105	1
1	140	1
1	155	1
1	175	1
1	190	1
1	205	1
1	220	1
1	235	1
2	260	1
2	290	1
2	315	1
2	345	1
2	370	1
2	400	1
2	425	1
2	455	1
2	490	1
2	530	1
2	565	1
2	605	1
2	645	1
1	675	1
1	705	1
1	730	1
1	765	1
1	795	1
1	820	1
1	845	1
1	875	1
1	905	1
		1
		1
		1
		1
		1
		1
		1
		1
		1
		1
		1
		1
		1

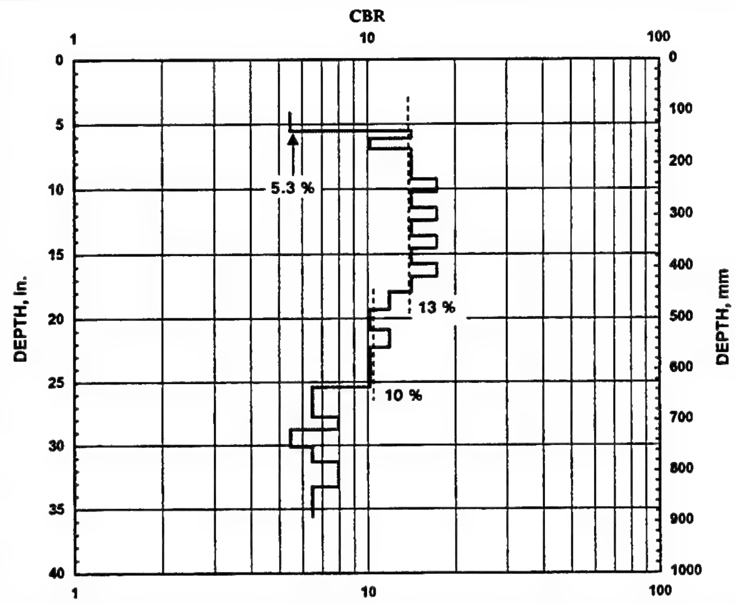


Figure 36. DCP measurement on the sand shoulder of experiment section two

DCP TEST DATA

File Name: DCP

Project: *Experiment Section 2*
Location: Item 2 East Wheelpath

Date: 4-Jun-98
Soil Type(s): SP SUBGRADE

Hammer
- ○ 10.1 lbs.
- ● 17.6 lbs.
- ○ Both hammers used

Soil Type
- ○ CH
- ○ CL
- ● All other soils

No. of Blows	Accumulative Penetration (mm)	Type of Hammer
0	0	1
5	20	1
5	40	1
5	65	1
5	100	1
4	125	1
4	150	1
4	175	1
4	205	1
4	240	1
4	275	1
4	300	1
4	325	1
4	350	1
4	375	1
4	400	1
4	425	1
4	445	1
4	475	1
4	500	1
4	525	1
4	545	1
4	570	1
4	590	1
4	610	1
4	630	1
4	650	1
5	675	1
5	700	1
5	730	1
5	765	1
4	790	1
4	820	1
4	855	1
4	890	1
4	925	1
		1
		1
		1
		1
		1
		1
		1

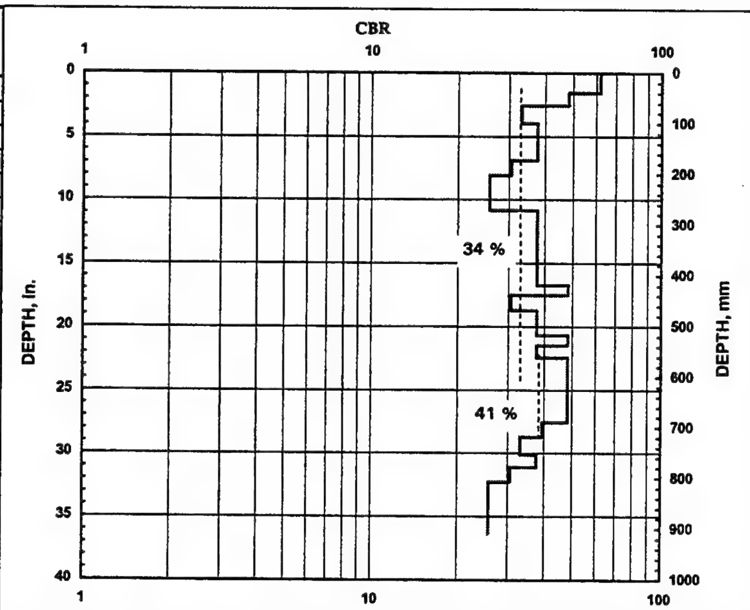


Figure 37. DCP measurement in item 2 of experiment section two

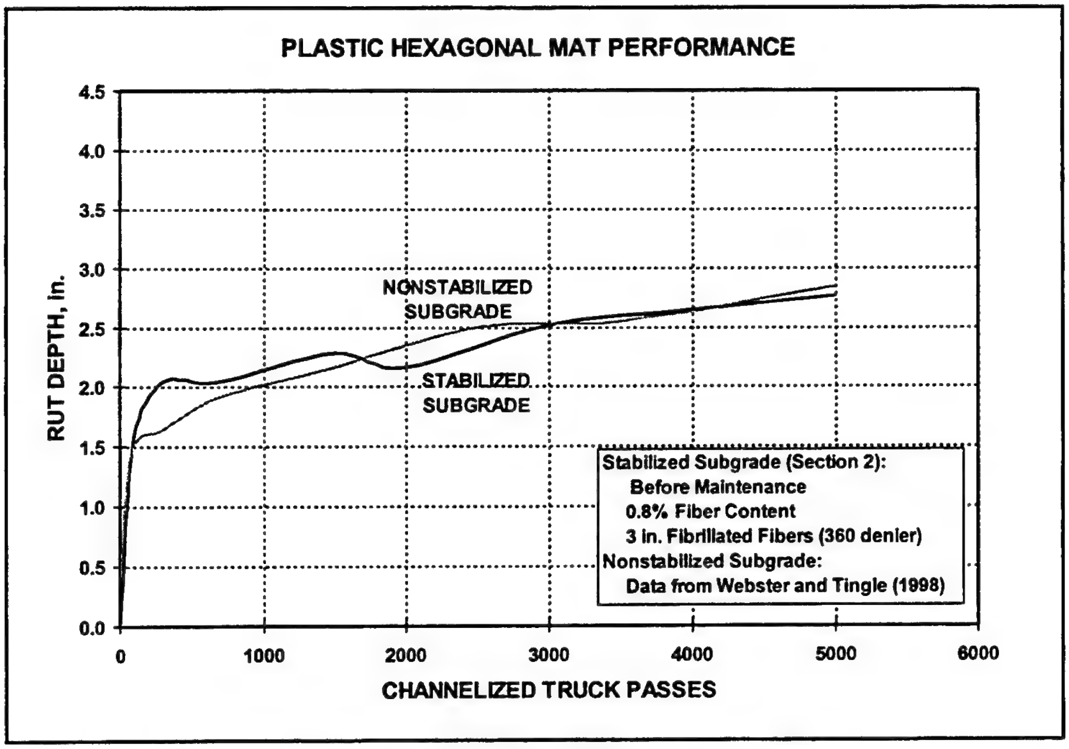


Figure 38. Plastic hexagonal mat performance over stabilized and nonstabilized concrete sand subgrades

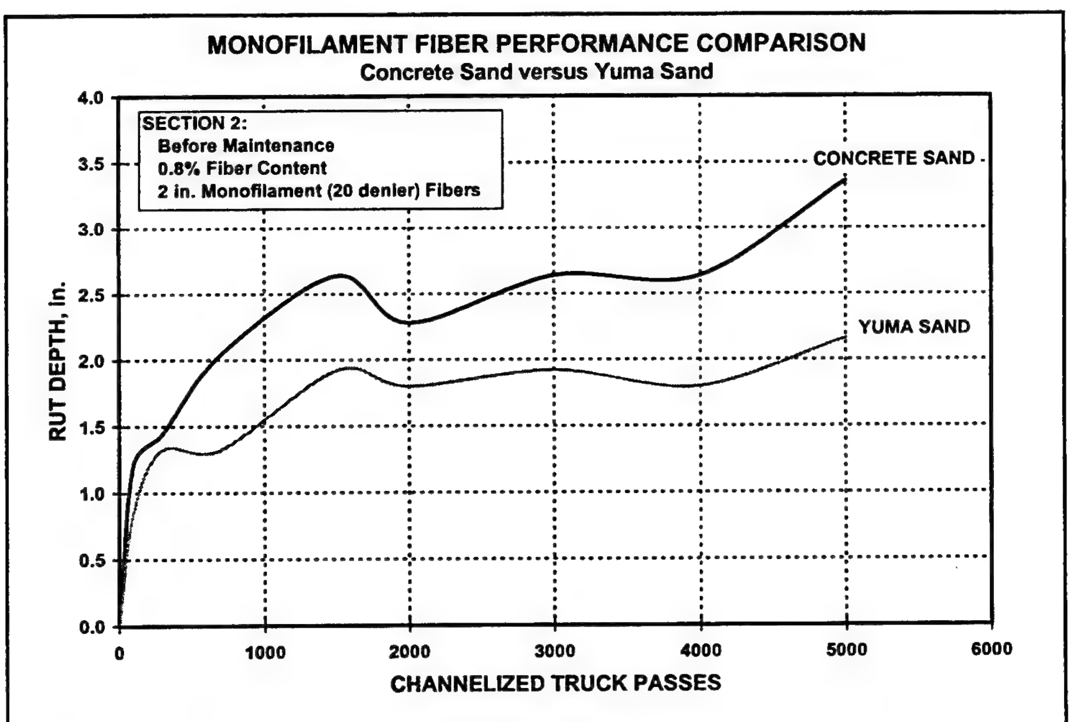


Figure 39. Comparison of concrete sand and Yuma sand items

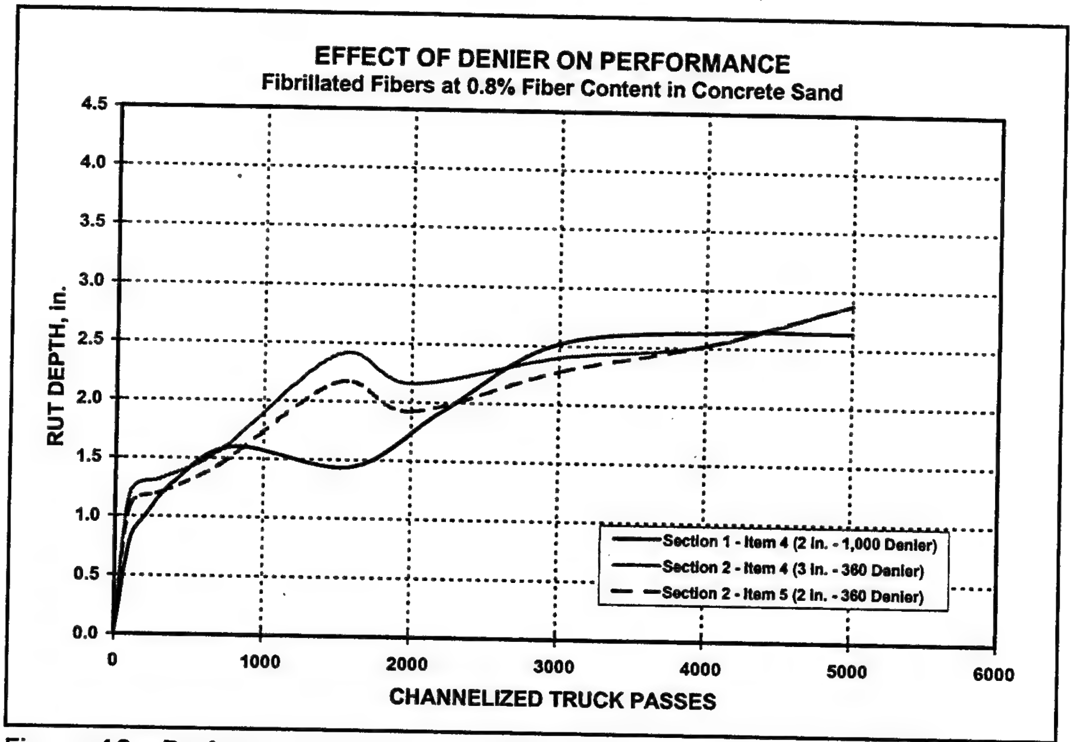


Figure 40. Performance comparison of two deniers of fibrillated fibers

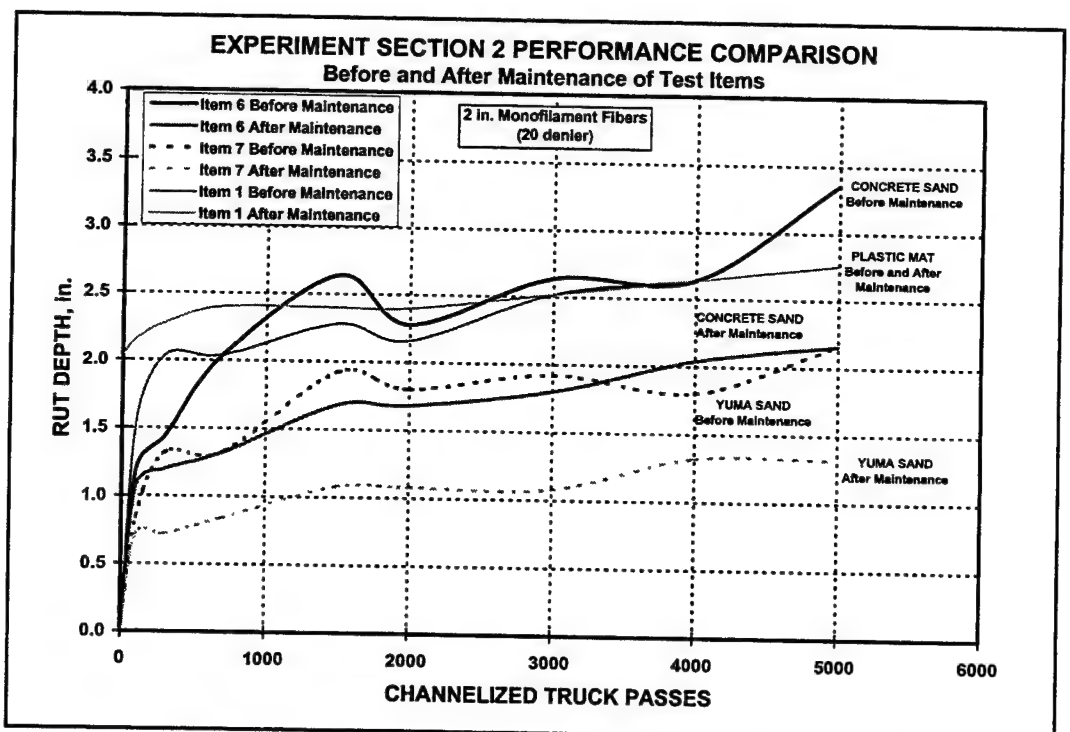


Figure 41. Effect of maintenance on items 1, 6, and 7 of section two

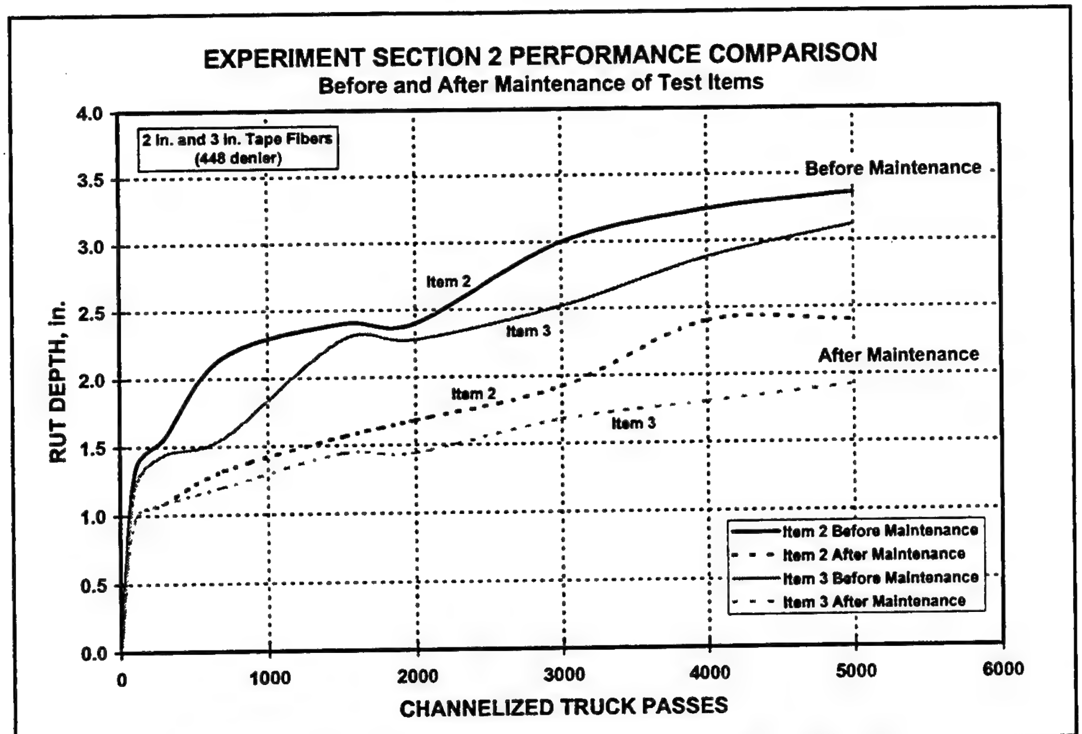


Figure 42. Effect of maintenance on items 2 and 3 of section two

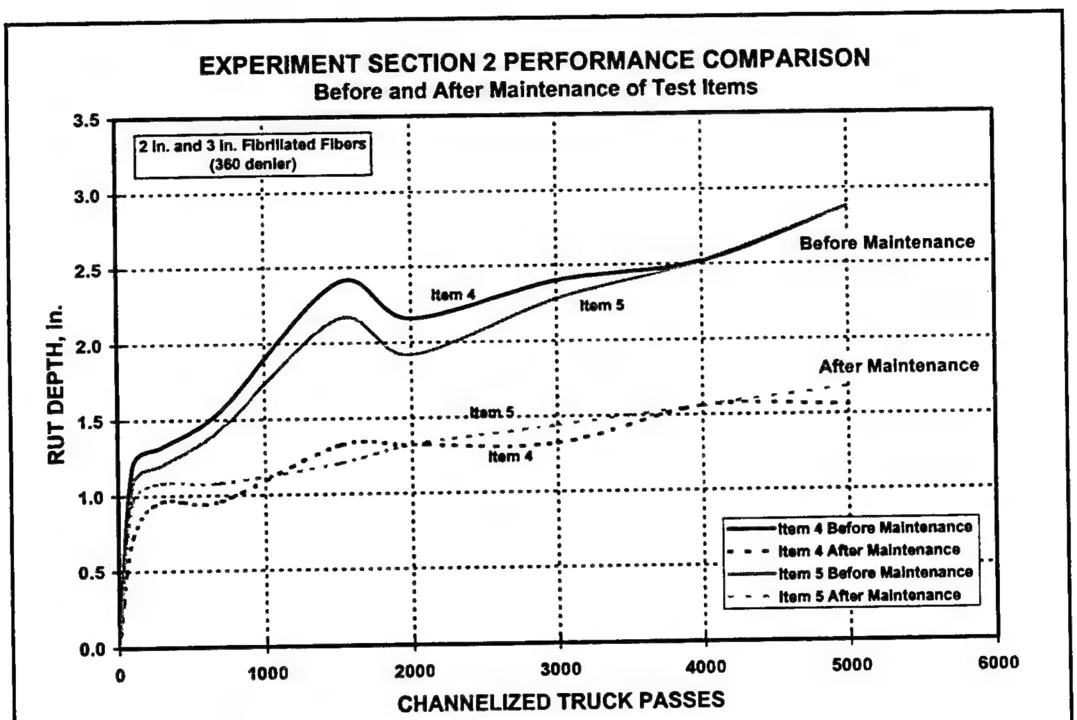


Figure 43. Effect of maintenance on items 4 and 5 of section two

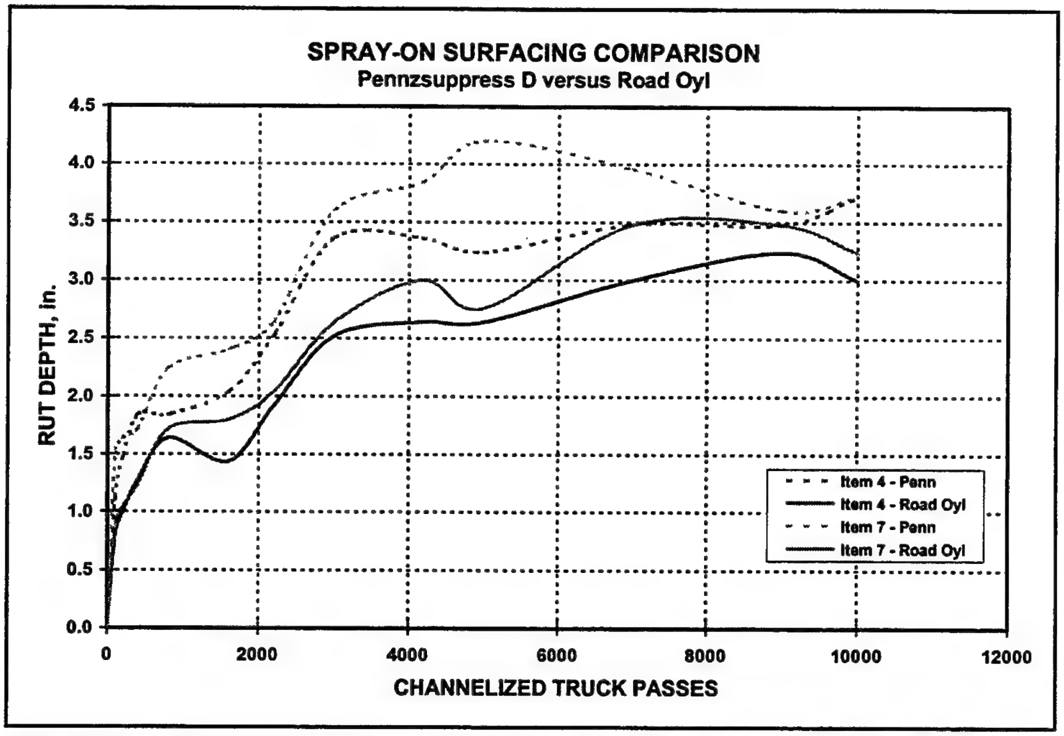


Figure 44. Comparison of spray-on surfacings, Pennzsuppress D versus Road Oyl

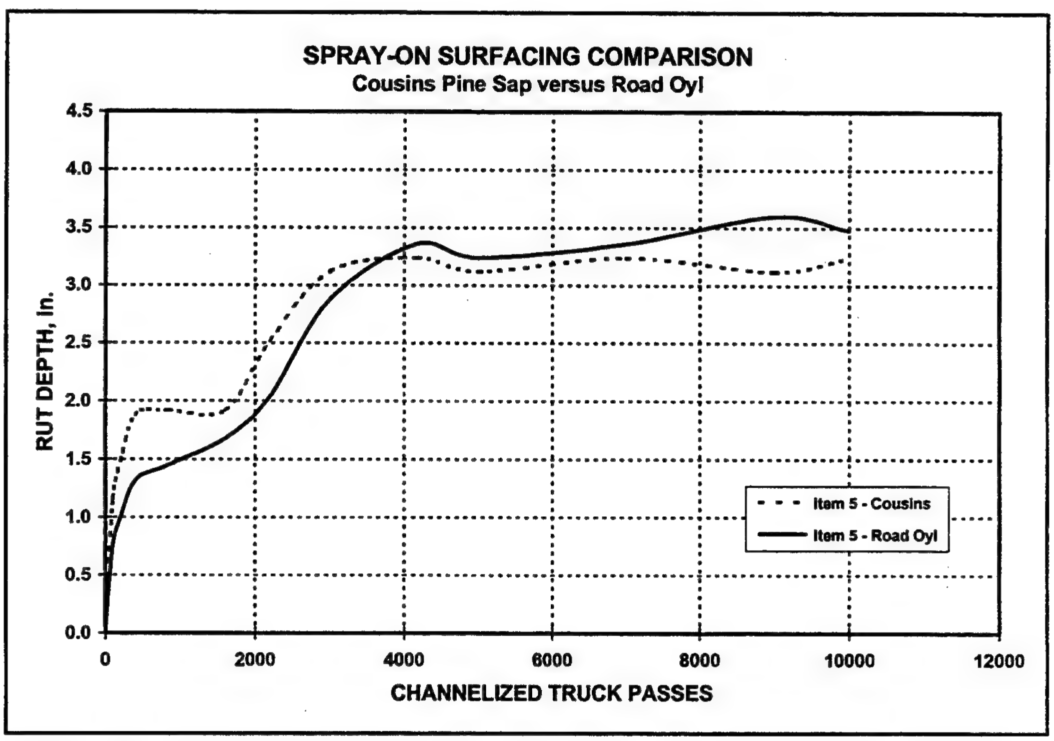


Figure 45. Comparison of spray-on surfacings, Cousins Pine Sap Emulsion versus Road Oyl

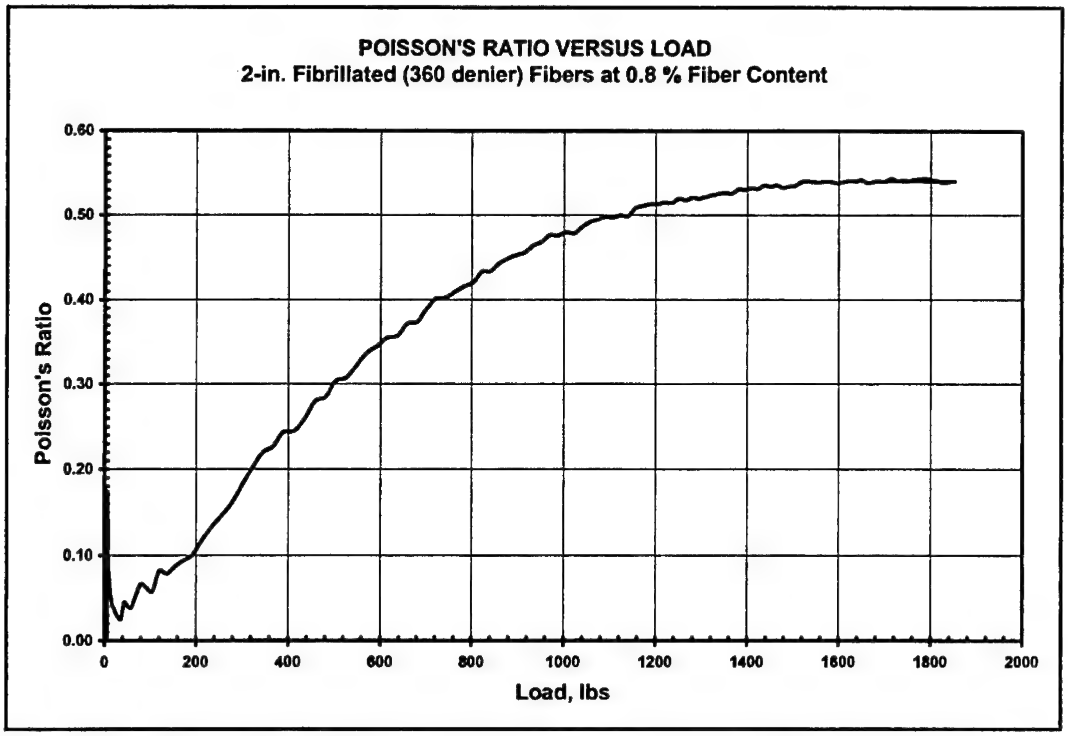


Figure 46. Typical plot of Poisson's ratio versus load for fiber-stabilized sand materials

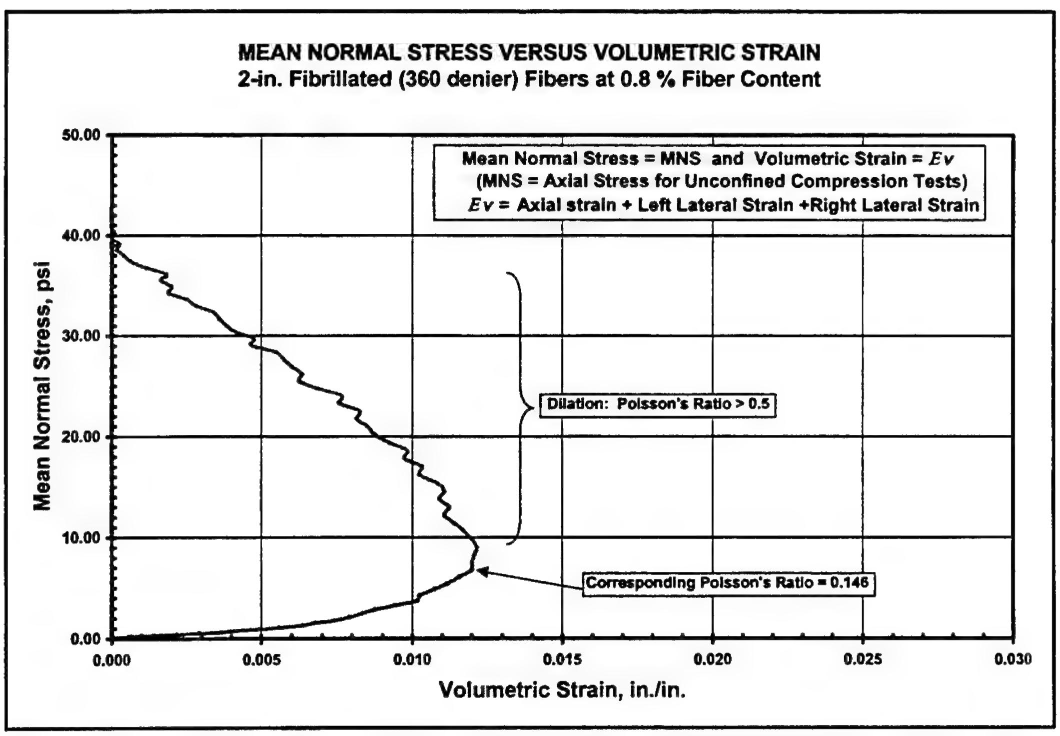


Figure 47. Typical plot of mean normal stress versus volumetric strain for fiber-stabilized materials

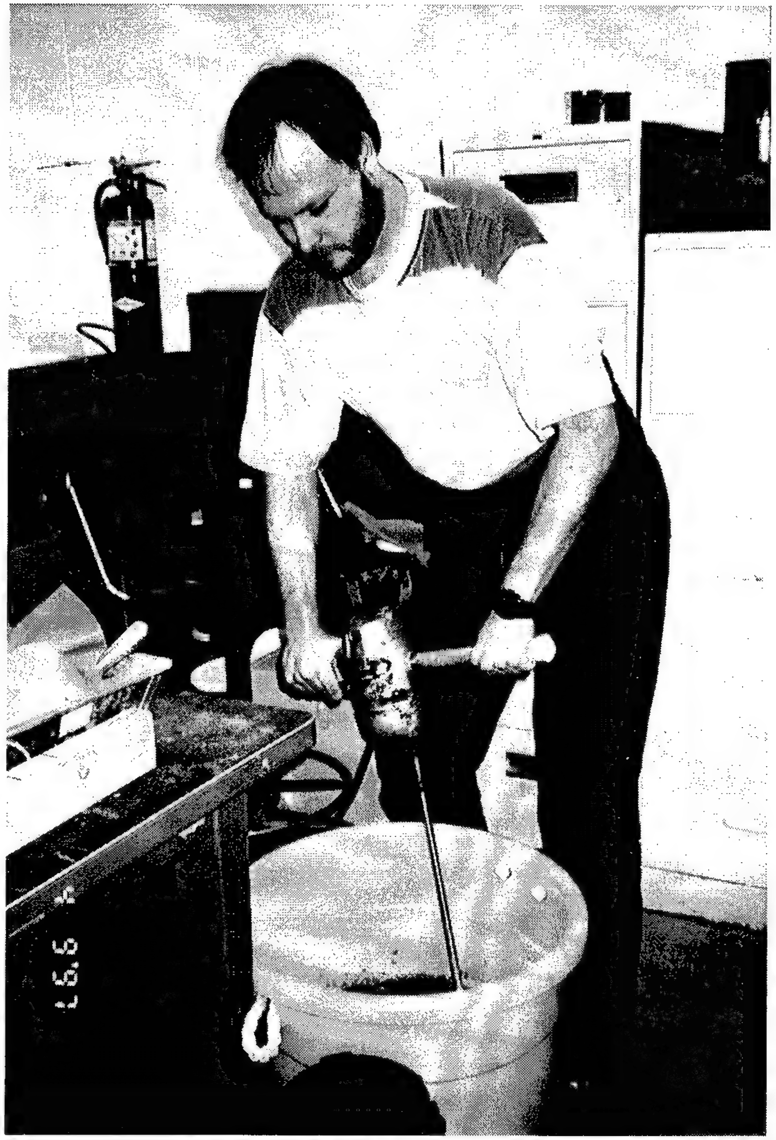


Photo 1. Mixing fibers into the sand in the laboratory

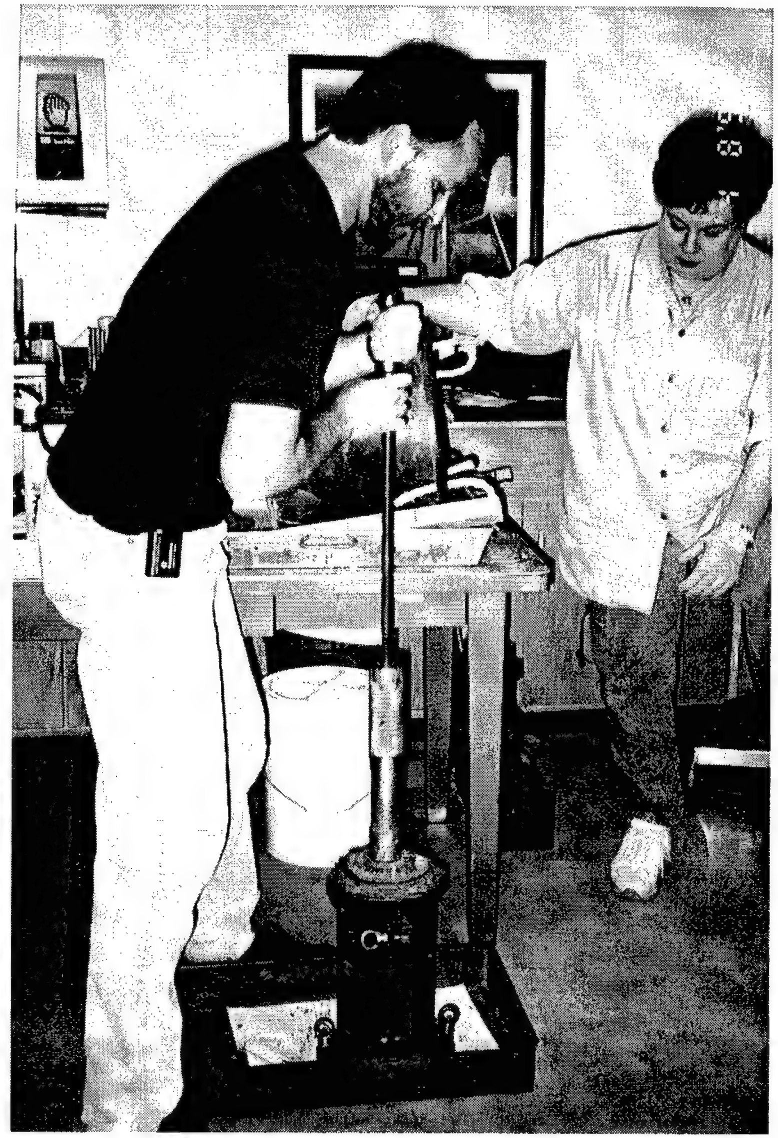


Photo 2. Compacting laboratory test specimens

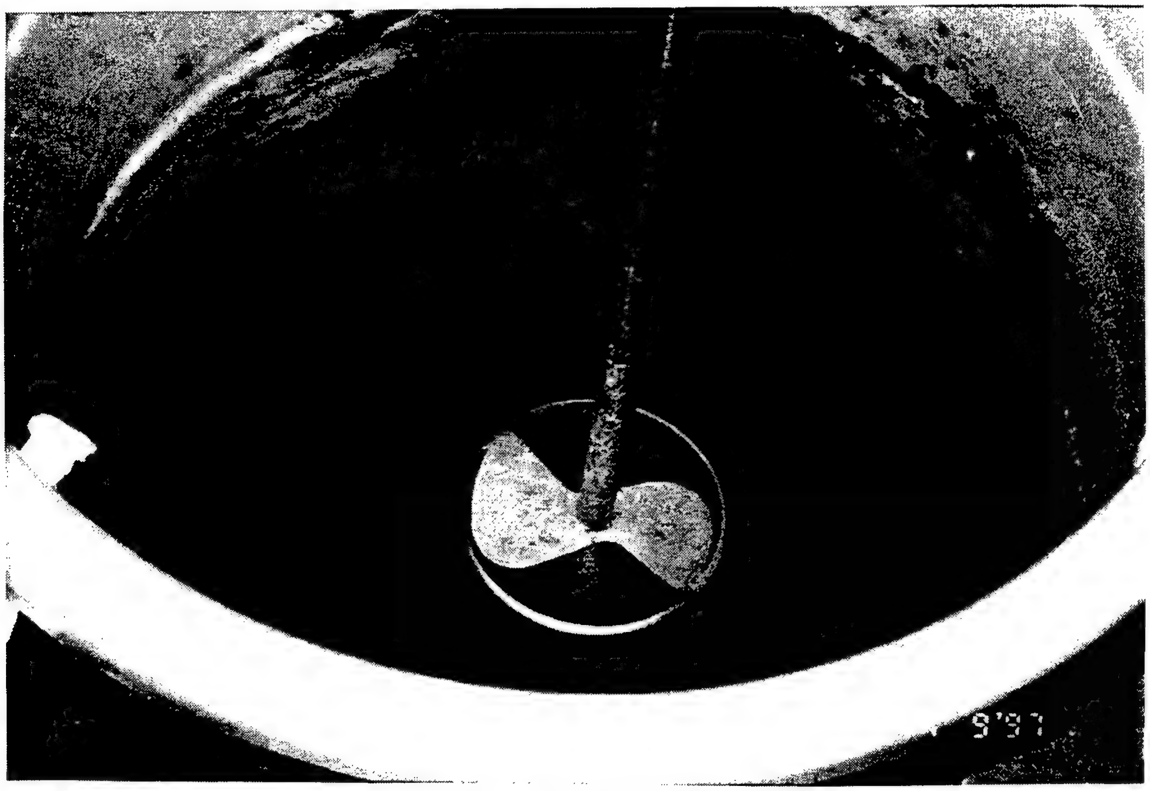


Photo 3. Fibers mixed in concrete sand in the laboratory

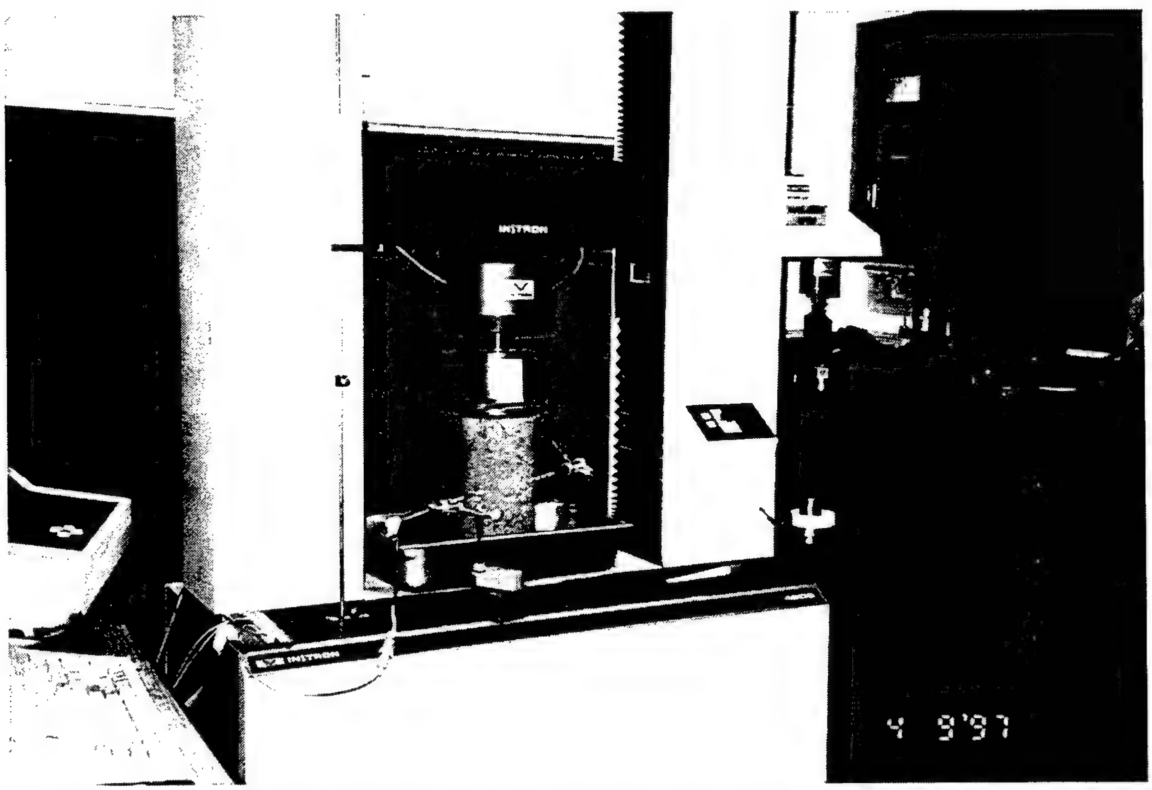


Photo 4. Laboratory unconfined compression test setup

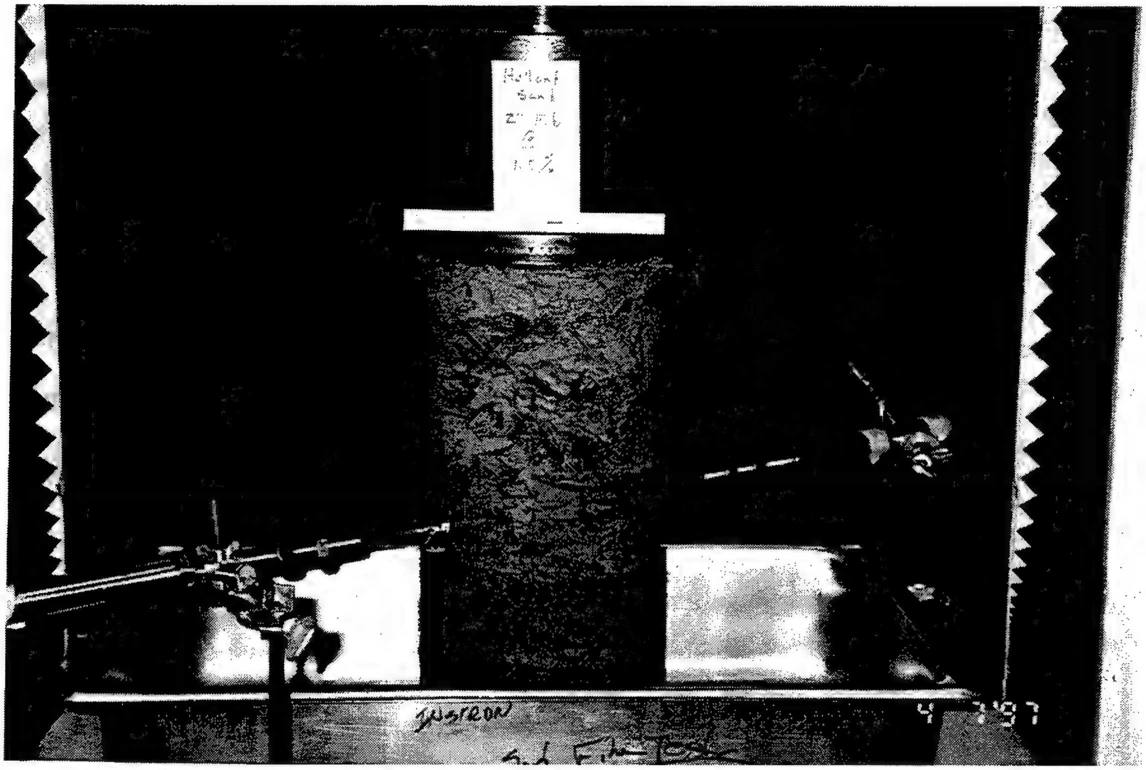


Photo 5. 2-in. fibrillated fibers at 1.0 % fiber content in Holland LZ silty sand prior to testing

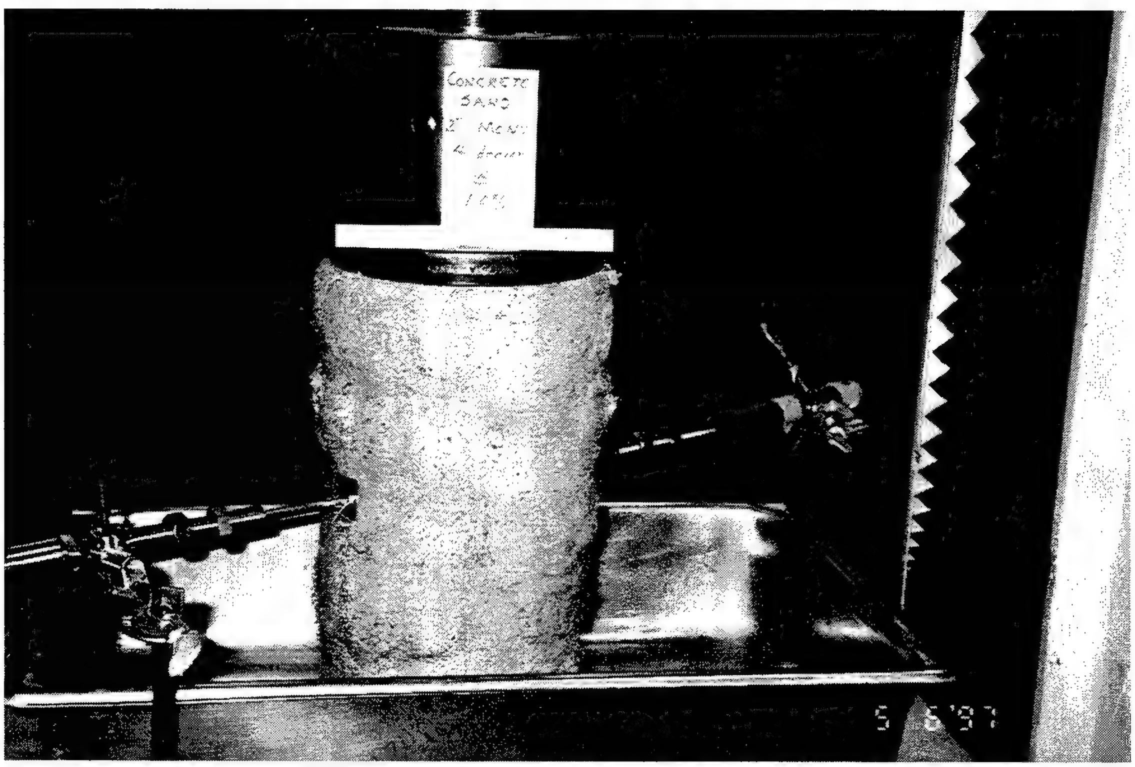


Photo 6. Test on 2-in. monofilament (4 denier) fibers at 1.0 % fiber content in concrete sand

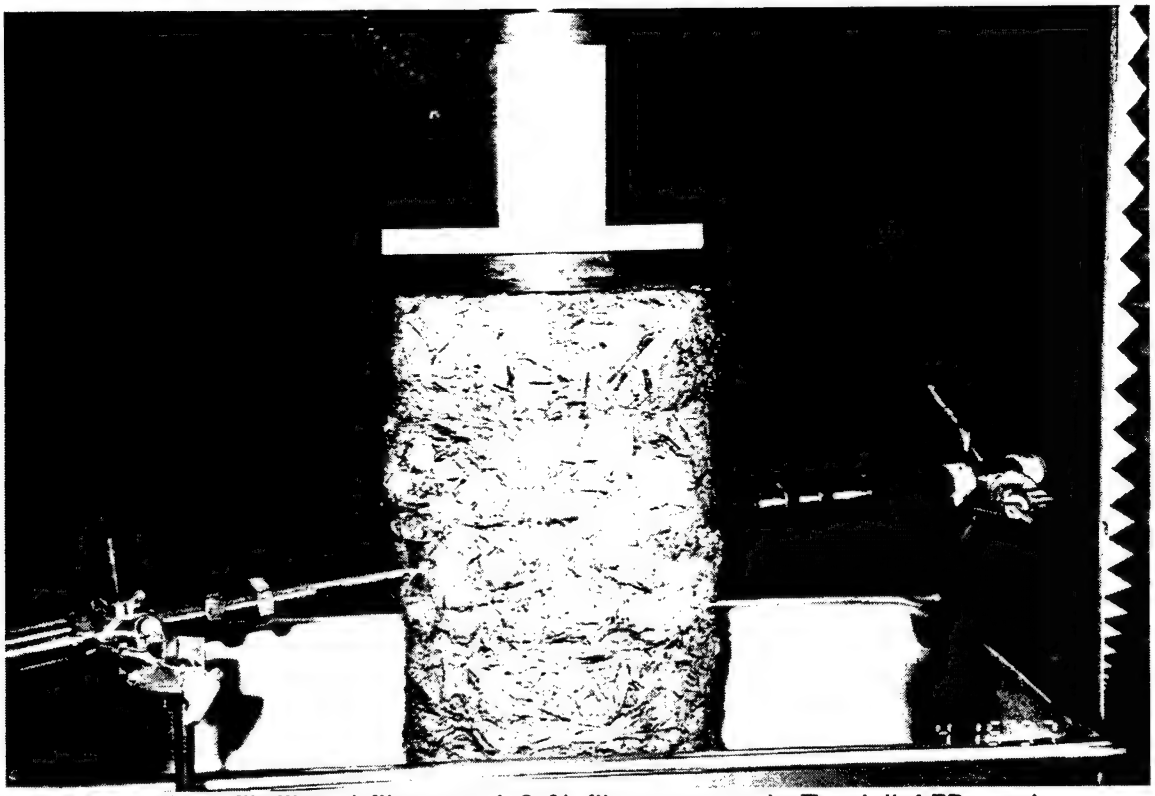


Photo 7. 2-in. fibrillated fibers at 1.0 % fiber content in Tyndall AFB sand during testing.

Photo 8. Sand and monofilament fibers prior to mixing in the staging area

Photo 9. Field mixing of monofilament fibers and concrete sand

Photo 10. Uniform mixture of tape fibers in concrete sand

Photo 11. Leveled experiment item prior to compaction

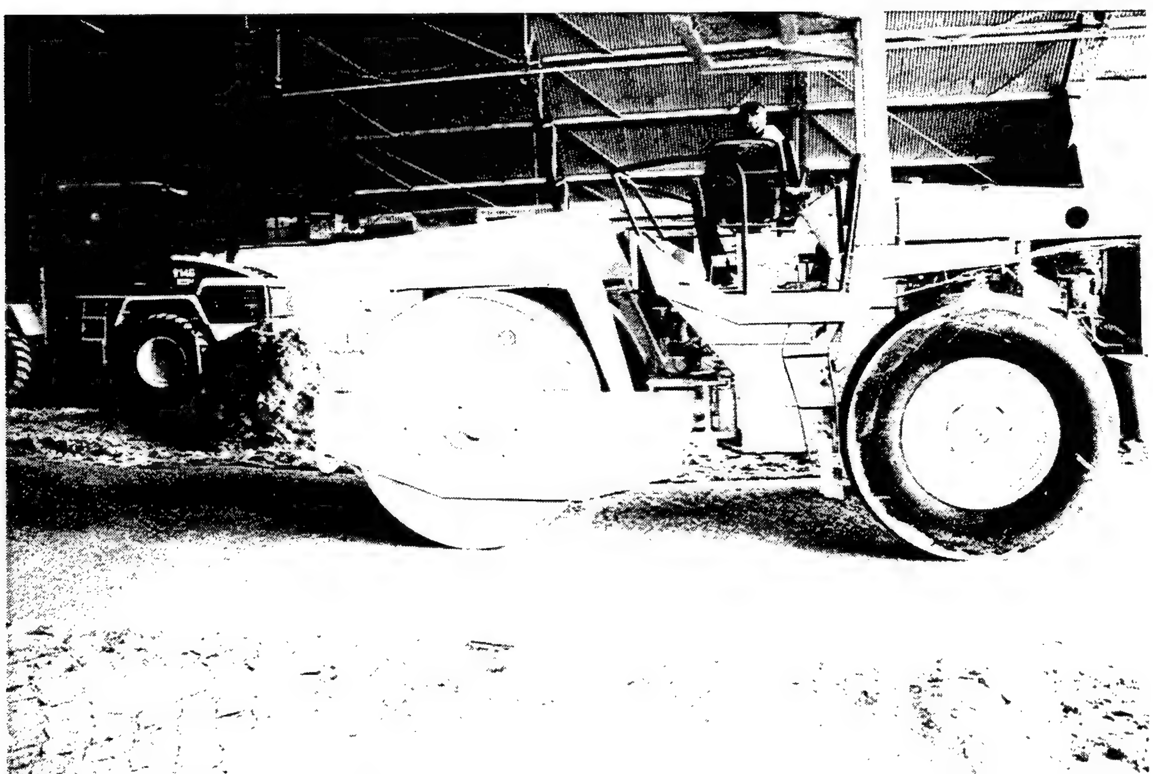


Photo 12. Field compaction of experiment item

Photo 13. Application of spray-on surfacings at 1 gsy

Photo 14. Completed experiment section one

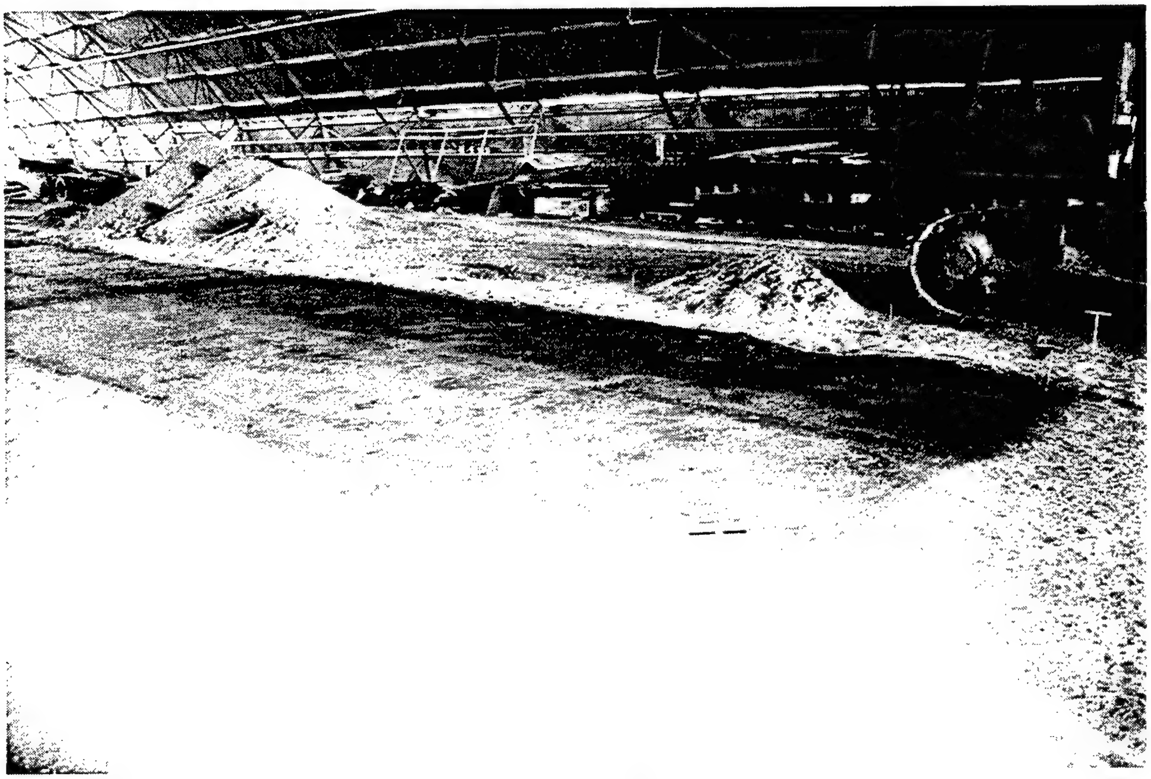


Photo 15. Completed item of experiment section two

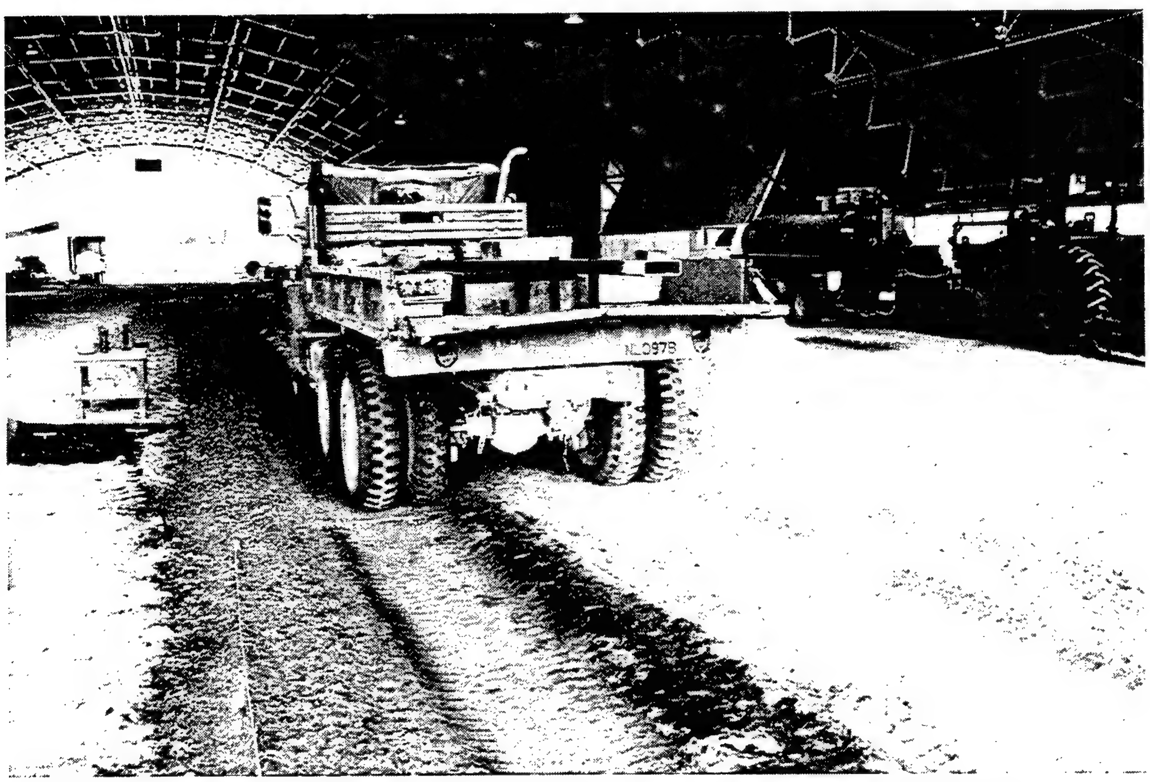


Photo 16. M923 5-ton military truck trafficking experiment section one

Photo 17. Rut depth measurements on item 1 of experiment section one

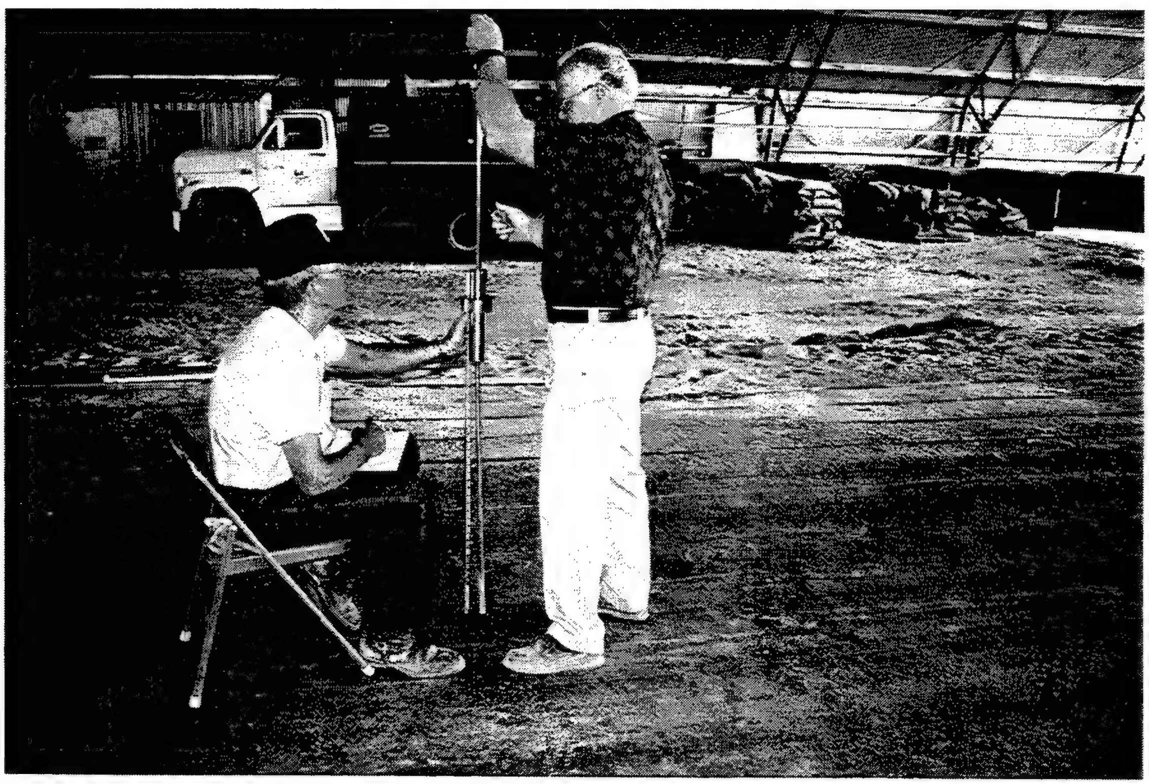


Photo 18. Typical DCP measurements on experiment sections

Photo 19. Item 1 of experiment section one after 10,000 truck passes

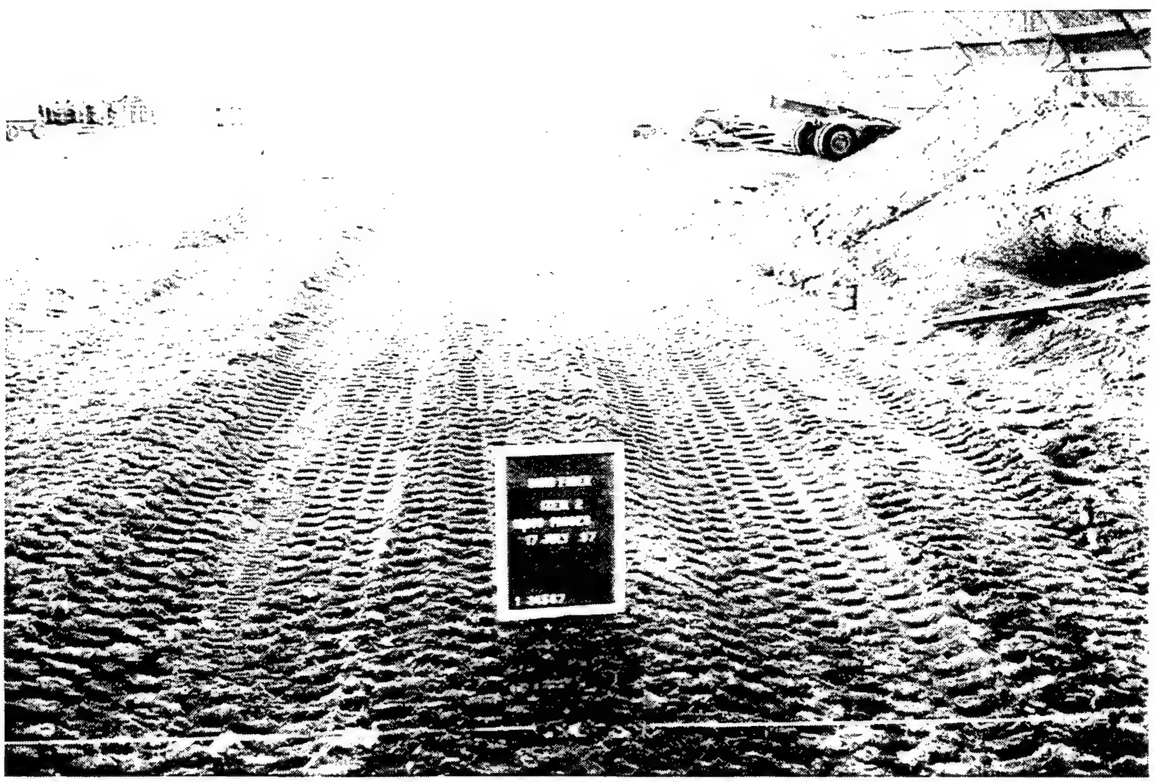


Photo 20. Item 2 of experiment section one after 10,000 truck passes

Photo 21. Item 3 of experiment section one after 10,000 truck passes

Photo 22. Item 4 of experiment section one after 10,000 truck passes

Photo 23. Item 5 of experiment section one after 10,000 truck passes

Photo 24. Item 6 of experiment section one after 10,000 truck passes

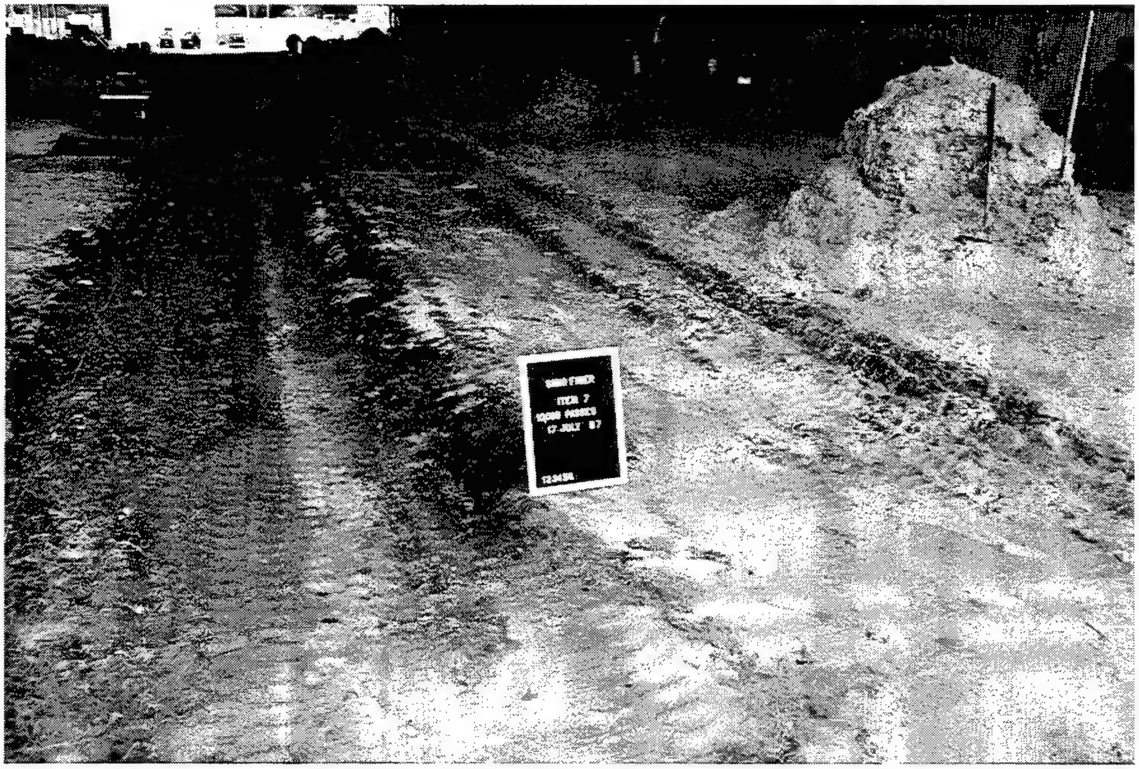


Photo 25. Item 7 of experiment section one after 10,000 truck passes

Photo 26. Item 1 of experiment section two -- 5,000 passes after maintenance

Photo 27. Item 2 of section two -- 5,000 truck passes after maintenance

Photo 28. Item 3 of section two -- 5,000 passes after maintenance

Photo 29. Item 4 of section two -- 5,000 truck passes after maintenance

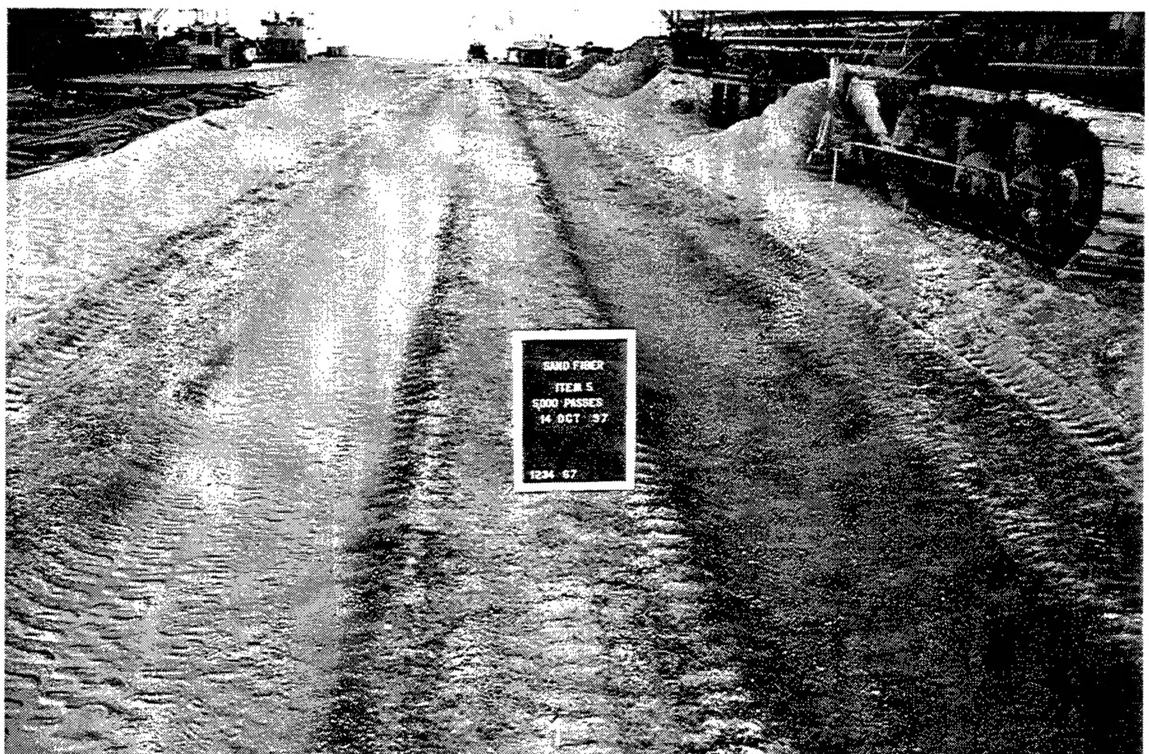


Photo 30. Item 5 of section two -- 5,000 passes before maintenance

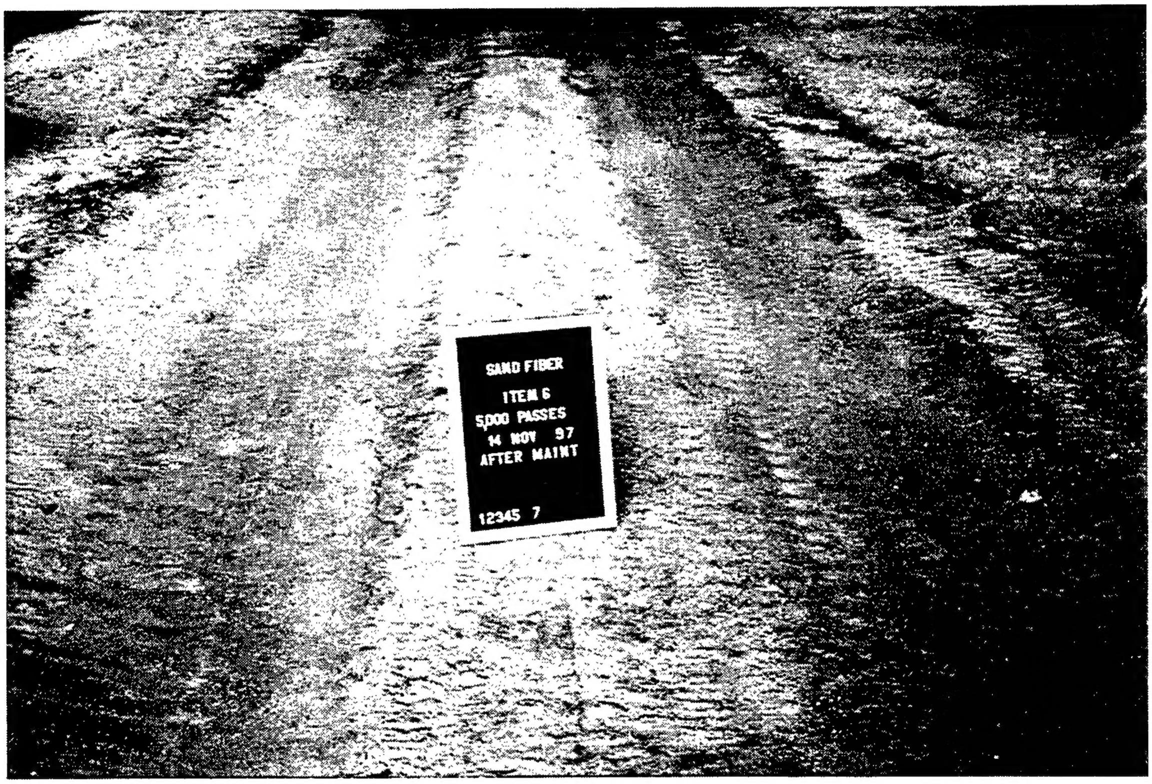


Photo 31. Item 6 of section two -- 5,000 truck passes after maintenance

Photo 32. Item 7 of section two -- 5,000 passes after maintenance

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1999

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Discrete Fiber Reinforcement of Sands for Expedient Road Construction

5. FUNDING NUMBERS

6. AUTHOR(S)
Jeb S. Tingle, Steve L. Webster, Rosa L. Santoni

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report GL-99-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineer
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes laboratory and field experiments conducted using discrete synthetic fibers to stabilize sands for expedient road construction. Unconfined compression tests were conducted as an index of material performance to identify the effects of fiber type, length, content , denier, and sand type on load-bearing capacity. Field sections consisting of 8-in. fiber-stabilized layers over a sand subgrade (SP) were constructed and trafficked to validate the laboratory results under actual field conditions. Experiment items were trafficked with 10,000 passes of a 41,600-lb 5-ton military truck.

Test results showed that fiber-reinforced sand materials are capable of providing structural support to military traffic over sand subgrades. The results revealed optimum stabilization parameters, practical construction technique, and effective maintenance procedures. Design, construction, and maintenance guidance are provided for using fiber-reinforced materials to support substantial amounts of military traffic.

14. SUBJECT TERMS

Construction platforms	Expedient roads	Road construction
Contingency pavements	Fiber reinforcement	
Discrete fibers	Logistics-over-the-shore	

15. NUMBER OF PAGES
110

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		